Analyzing Remediation Technologies for
Department of Energy Sites Contaminated
With DNAPL Pollutants

THESIS

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AFIT/GOR/ENS/97M-17

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THESIS APPROVAL

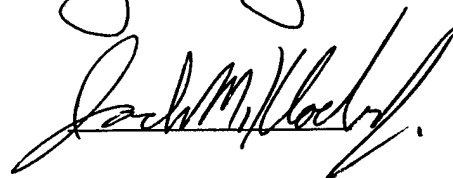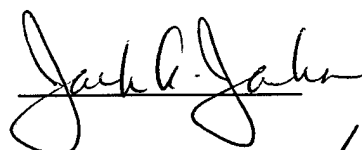Student: Anthony F. Papatyi, Captain, USAF   Class: GOR-97M
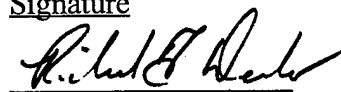
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Abstract

The Department of Energy is in the process of conducting a Remedial Investigation/Feasibility Study for a site contaminated with Dense Non-Aqueous Phase Liquid (DNAPL) pollutants at their Paducah Kentucky facility. A major part of this effort is the screening of alternative technologies. This thesis effort focuses on acquiring insight into a number of remediation technology trains that are candidates for the Paducah site. This insight is used to recommend and justify the screening of candidate technology trains. The research makes use of two decision analysis models (one is deterministic, the other is probabilistic) built to provide a quantitative assessment of the candidate technology trains. Dominance considerations and multi-attribute utility theory are utilized to make the quantitative assessments and to gain insight into each candidate technology train.

The results of the analysis provide the DOE with a rational justification for screening 55 of the 58 candidate technology trains from further consideration. This represents a 95% reduction in the number of technology trains that are under consideration for remediating the Paducah site.

Analyzing Remediation Technologies for Department of Energy Sites Contaminated With DNAPL Pollutants

I. Introduction

1.1 General Issue

One of the most difficult environmental challenges facing the United States is the restoration of sites contaminated with Dense Non-Aqueous Phase Liquids, (DNAPLs). DNAPLs are toxic, immiscible fluids that have a density greater than water. DNAPLs are typically segregated into four distinct categories: 1) halogenated hydrocarbon solvents, 2) creosote based wood-treating oils, 3) Polychlorinated Biphenyls (PCBs), and 4) pesticides [Cohen and Mercer, 1993, 2-2].

The contaminant requires special attention because of its physical properties, unique migration pathways, and toxicity. Due to the widespread production, use and transport of these chemicals over the past 180 years, it is estimated that there are thousands of sites contaminated by DNAPLs. These sites range from coal tar contaminants that were generated during the mid 1800's to degreasing agents used in modern manufacturing facilities [Cohen and Mercer, 1993, 3-1]. Cohen and Mercer note that in 1988 there were 55 wood preserving sites listed on the National Priorities List (NPL). These sites are contaminated with creosote and/or coal tar. Additionally, by 1990, 17% of the NPL sites were classified as PCB sites. These sites (and many others

yet to be detected) contain an estimated 290 million pounds of PCBs that have not been destroyed by incineration [Cohen and Mercer, 1993, 3-19].

At some sites, DNAPL presence has been immediately detected. At others, because of the limited volume of DNAPL, the source and amount of the DNAPL contaminant is difficult to determine. As a result, the presence of DNAPL is often detected at sites where DNAPL contamination was not initially suspected [Cohen and Mercer, 1993, 3-1]. Such a discovery can compromise a remediation process that did not anticipate the presence of DNAPLs.

At present, there are fifteen confirmed or suspected DNAPL sites at various Department of Energy (DOE) complexes across the United States [DOE Technology Summary, August 1996: 55].

To address the contamination at these sites, a number of competing technologies are being developed for remediation and/or containment. Each of these technologies is in varying stages of development, and must be objectively evaluated for application at known and projected DNAPL sites. For this reason, the DOE Subsurface Contaminants Focus Area has requested an analysis that will provide insight into the selection of candidate technology trains that may be used to remediate DNAPL sites. In order to provide this analysis, the decision situation surrounding the selection of technologies must be appropriately modeled and analyzed.

This thesis effort focuses on the development of two DA models that provide the decision makers with insight into the complex process of selecting remediation trains. The two models built were used to 1) screen candidate trains, and 2) gain insight into the risk

aspects of the reduced set of screened trains. The results of these models will provide the DOE with a systematic analysis and insight into a number of competing remediation technology trains. The demonstration analysis will focus on the WAG6 site in the C-400 area at the Paducah, Kentucky DOE complex.

1.2 Background

The Subsurface Contaminants Focus Area is tasked with developing technologies that will characterize, remediate and/or contain, and monitor contaminated subsurface sites. This charge includes DNAPL sites. The term "remediate" is used to indicate that the contaminated site will be cleaned up or controlled to a level that will provide overall protection of human health and the environment as required by the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) [DOE/OR/07-1243&D3: 9-3]. The term "contain" is used to describe any process that is used to prevent the contaminant from spreading. A typical containment technique is to pour a concrete barrier around the contaminated site, creating a physical barrier that the contaminant cannot penetrate. The term "technology" is used to denote techniques, methods, or processes that may be useful for characterizing, remediating, containing, and/or monitoring a contaminated site.

Different technologies are used during each stage of the cleanup process of a DNAPL site. For example, Electro-osmosis is a remediation technology sometimes used to remove DNAPL contaminants from low permeability media. This technology uses electrodes installed into the ground. An electrical charge flowing between electrodes

causes contaminant migration. Once the contaminant has migrated in sufficient quantities, it may be either adsorbed or destroyed in-situ [DOE Technology Summary, August 1996: 86].

A "technology train", or simply a "train", is used here to identify a number of technologies that are grouped together to form a complete technology package that will remediate or contain a site. The tactics that make up a specific technology train are the selected containment, removal, or remediation technologies.

At present, the Subsurface Contaminants Focus Area has no standardized means for selecting strategies to cleanup DNAPL contaminants at specific sites. A great deal of uncertainty surrounds these decisions. It is not certain which developing technologies will succeed; which will fail (i.e. a technology may not work as anticipated and the time and money invested in that particular effort will have been wasted); or the true cost and/or time each emerging technology will require to become fully operational at a specific contaminated site. Additionally, there is a substantial uncertainty related to the sub-surface geology. Soil permeability, geologic formations, and contaminant quantities and densities are a few of the sources of uncertainties that must be taken into account when deciding upon a strategy for a specific site. These uncertainties, combined with the combinatorial nature of selecting sets of technologies to makeup a train for a particular site, make this decision quite complex.

1.3 Problem Statement

The DOE requires a decision support system which incorporates operational risk for assessing remediation technology strategies at DNAPL sites. The decision support system will be applied at the WAG6 site in Paducah, Kentucky, to assist the DOE in the screening process of remediation trains. Other risk elements such as health and safety, or environmental, have not been incorporated in this modeling effort at the request of this project's sponsor due to previous technology screens conducted for the WAG6 site.

1.4 Research Objective

The primary objective of this research is to provide the DOE with insight into the candidate technology trains that are being considered for remediating sites contaminated with DNAPL pollutants. The approach is to build the decision support system using a screening model and a probabilistic model, with interaction from key DOE operational and decision making personnel. The screening model will be used to analyze the decision situation with a focus on screening the candidate trains to a set of top contenders. The probabilistic model will be used to assess the top contenders with respect to uncertainty and risks. The models are demonstrated by analyzing the WAG6 site for a specified spill volume. The main value of the models is to provide insight that is useful in justifying the screening of technology trains. This insight is gained through the use of utility theory, dominance considerations, and risk and sensitivity analysis. It will assist the DOE decision makers in their quest to identify and select a "best" technology train.

1.5 Scope of Thesis

The scope of this effort will be restricted to the following areas:

- A comprehensive literature review to investigate the following topics:

  - Decision analysis - with specific attention to geologic applications

  - Multiattribute Utility Theory (MAUT)

- The development of DA tools that will accommodate life cycle cost, time, stochastic performance measures, and decision maker preferences for selecting remediation or containment technology trains for DNAPL contaminated sites

- A thorough sensitivity analysis of the results of the WAG6 site specific analysis for a specified spill volume

- Conclusions regarding the model and the sensitivity analysis

- Recommendations for further research

1.6 Overview

Chapter 2 provides a discussion of the current literature relating to this topic. Chapter 3 contains a discussion of the methodology used to develop the DA models. The development of the methodology is based on the information contained in Chapter 2. Chapter 4 discusses the output of the models and contains a thorough sensitivity analysis of the candidate trains and their key variables. Chapter 5 consists of the conclusions and recommendations that can be drawn from the analysis. Additionally, a detailed appendix is included to aid in the full understanding of the DA models and the nuances of their structure.

II. Literature Review

2.1 Introduction

The purpose of this literature review is two fold: 1) To provide the reader with an understanding and appreciation of the subject areas surrounding the selection of remediation trains for sites contaminated with DNAPL pollutants and 2) To investigate and report on other efforts that are similar to the one undertaken here. As such, an overview of DA is first presented. This is followed with a discussion of Multiattribute Utility Theory (MAUT). Because of the similarities between the gas and oil industry and environmental restoration/remediation of DNAPLs (both are trying to remove specific materials from the sub-surface) a discussion of these two areas and their use of DA/MAUT is also presented .

2.2 Decision Analysis

Decision analysis, according to Clemen (page 6), is an iterative process used to provide insight into a decision situation, its pertinent objectives, and its potential alternatives. The process begins with a clear identification and understanding of the decision situation. Once this identification is made, the second step is to determine the objectives of the decision(s) and the values of the Decision Maker (DM). To maximize the benefits of the DA process, the objectives and values must be stated as precisely as possible.

The next step in the process is to identify the potential alternatives [Clemen, 1996: 6]. Typically, the identification of alternatives makes use of the previously stated

objectives. There are a number of methods that have been used in the past to create these alternatives; the three most popular are discussed here.

Keeney suggests an iterative process that selects one objective at a time while ignoring the rest, and inventing alternatives or scenarios that make that objective look as good as possible [Keeney, 1992: 210].

Another possibility, also suggested by Keeney, is to use an approach that puts all of the stated objectives at their most favorable level. This leads to the ideal alternative. This alternative can then be analyzed to determine which constraints are holding one back from this ideal alternative [Keeney, 1992: 221].

Howard suggests the construction of a strategy generation table to assist in the identification of alternatives. The idea behind the strategy generation table is to list alternatives with a specific objective in a column below that objective. Once each objective has an exhaustive list of alternatives, a table is formed with the columns representing objectives, and the rows representing alternatives for each objective. After the table is constructed, strategies can be selected and analyzed in an easily understood and visual manner [Howard, 1988:684].

Other ideas suggested by Clemen for generating alternatives include idea checklists, morphological forced connections, means objective networks, brainstorming, and metaphorical thinking [Clemen, 1996: 200-207].

The next step in the DA process, as outlined by Clemen, is to decompose and model the problem, decisions, uncertainties, and preferences. This step is critical and must be conducted with the involvement of the DM. The primary decomposition and modeling

tools used are influence diagrams and decision trees. Both of these tools provide visual insight into the decision(s) and problem(s) at hand.

An Influence Diagram provides a relatively simple way to visualize a decision situation [Clemen, 1996: 50]. The Influence Diagram makes use of three simple block shapes to represent specific pieces of the decision situation. Figure 2.1 summarizes the three shapes and their significance.

Decision Node	The decision node indicates that a decision must be made: i.e. which alternative, or Yes/No.
Uncertainty Node	The uncertainty node indicates that the outcome of a specific event is not known with certainty.
Calculation or Value Node	The Calculation or Value node is used to perform calculations or to identify constants within a decision.
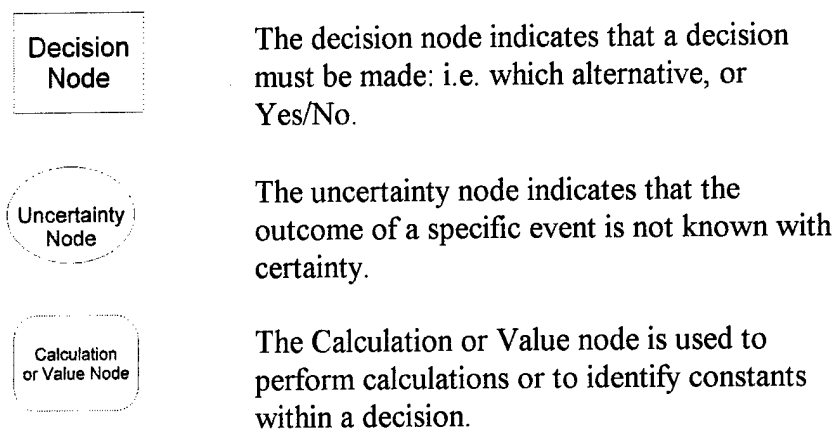
Figure 2.1 Influence Diagram nodes

An example of a decision situation is shown in Figure 2.2. In this figure, the decision is which of two remediation technology alternatives to select. The uncertainty indicates that the performance of the technology is an uncertain entity. The calculation or value node is used to calculate the expected level of cleanliness after the site has been remediated.
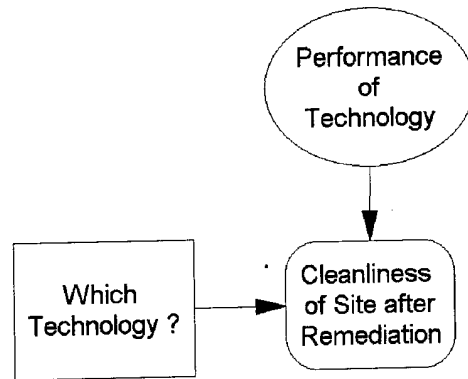
Figure 2.2 Decision Situation for a Simple Technology Selection

To expose the details of the decision situation, a decision tree is used. A decision

tree shows the mutually exclusive and collectively exhaustive outcomes that are possible

[Holloway, 1979:33]. An example of a decision tree representation of the Influence

Diagram shown in Figure 2.2 is shown in Figure 2.3.
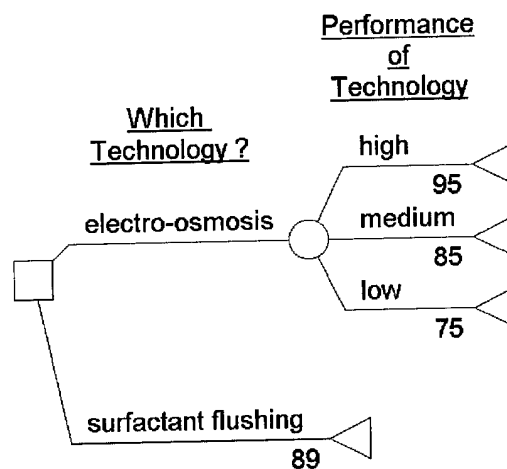
Figure 2.3 Decision Tree Representation

In the decision tree note that the square represents the decision, and the circle represents the uncertain node. The values or outcomes are listed at the tail of each branch of the tree.

The final steps in the DA process are to select the best alternative, and conduct sensitivity analysis to assure that the best alternative remains the preferred choice in the presence of potential deviations. Choosing the best alternative can sometimes be quite difficult, even when an obvious best choice surfaces based on an Expected Value (EV). Risk profiles, deterministic and probabilistic dominance, and sensitivity analysis tend to uncover subtleties related to the decision situation that may not be obvious by simply looking at EV [Clemen, 1996 123].

All of the steps described in the DA process are iterative, often requiring review at each step. Decision Maker attitudes and insights will change as a decision situation is modeled and the fog of the uncertainties surrounding a decision is reduced. It is, therefore, imperative that the overall goal of the decision situation be kept in view as the modeling and analysis process takes place [Clemen, 1996: 7].

2.3 Multiattribute Utility Theory

Multiattribute Utility Theory (MAUT) encompasses a broad range of topics that are aimed at gaining insight into decisions that contain many, and often times conflicting, objectives [Clemen, 1996: 532]. To understand and discuss MAUT, it is important to understand the relationship between objectives and attributes. Keeney defines an attribute of an objective as "the degree to which an objective is achieved" [Keeney, 1992: 100]. He goes on to state that attributes "should be measurable, operational, and understandable"

[Keeney, 1992: 112]. An example of the relationship between attributes and objectives is presented by Clemen. If, for example, one objective was to minimize costs, then the natural attribute scale would be dollars [Clemen, 1996: 532].

Another important concept that must be understood when discussing MAUT is that of additive utility functions versus utility functions with interactions. When an additive utility function is employed, it is assumed that each attribute has its own utility function and that the attributes are additive and independent. The additive utility function is a weighted average utility function of all of the individual attributes for a given problem [Clemen, 1996: 537]. For example, suppose that two objectives were stated as: 1) Minimize the cost of the project, and 2) Minimize the time necessary to complete the project. Clearly these are two potentially conflicting objectives. MAUT would be a good candidate for an evaluation technique for gaining insight into these two objectives. The attributes of these two objectives are: 1) cost (dollars) used to complete the project, and 2) time (months) required to complete the project. Each of these objective/attribute combinations possess their own utility function.

The additive utility function is simply a weighted average of the combination of the two individual utility functions. To determine the weights assigned to each piece of the utility function, it is necessary to ascertain the relative importance of each attribute. For example, is cost twice as important as time in completion of this hypothetical project? If so, then the weight for cost would be 0.667, and that for time would be 0.333. By convention, for the additive utility function, the weights must sum to 1.0 [Clemen, 1996: 537].

According to Clemen, when interactions between the attributes exist (i.e. attributes are not independent), the use of an additive utility function is not justified. One must consider a utility function that captures the interactions. The utility function shown in (2.1) is a general form of a utility function that contains interactions.

$$U(x,y) = c_1 + c_2 U_X(x) + c_3 U_Y(y) + c_4 U_X(x)U_Y(y) \qquad (2.1)$$

To use a utility function of this form, it is necessary to have seperability - i.e. the overall utility function can be broken into different pieces that, when put together, represent all of the different attributes and their interactions.

To assure that seperability exists, one must check for two independence levels: 1) Preferential Independence, and 2) Utility Independence. An attribute is preferentially independent of other attributes if *specific* outcomes of one are not dependent on the others. Likewise, an attribute is said to possess utility independence if preferences for uncertain choices between different levels of one attribute do not depend on the level of the other attribute(s) [Clemen, 1996: 581]. Both conditions must be satisfied if one is to use a decomposable utility function like the one shown in (2.1).

However, because of the difficulty in proving that these levels of independence hold, most applications, especially first cut ones, assume complete additive independence, and use an additive utility function without any serious adverse results [Clemen, 1996: 593 and Stewart, 1995: 254]. Following Stewart and Clemen's suggestion, the utility function used in this thesis, and described in Chapter 3, assumes that the attributes are independent, and makes use of an additive utility function.

2.4 Decision Analysis and MAUT Applied to Oil and Gas Recovery

The majority of the DA/MAUT related research in the oil and gas industry has been conducted with regards to oil exploration. As such, most of the discussion in this section is devoted to this topic. While this is not an exact 1 to 1 mapping to conducting DA/MAUT on the selection of alternative remediation technologies, there are similarities that apply to this research.

2.4.1 Oil Wildcatting

An example of the classic use of DA/MAUT in oil exploration is found in Holloway (pages 195 - 200). The decision situation presented is that of choosing between two sites for exploratory oil drilling. One sight is risky because of the level of uncertainty surrounding the quantity of oil that may exist. The other site is not as risky because it is known, with a fairly high probability, that it will produce at least a small amount of oil. Potential outcomes (quantity of oil retrieved and thus profits realized) are dependent on the amount of oil actually in the ground, the presence of a dome structure, and the cost of drilling each well. Only one well (site) may be drilled. Holloway demonstrates the use of conditional probabilities to gain insight into a DA problem, and how to calculate the value of information and its potential uses in gaining insight into a DA problem [1979: 195 - 200].

2.4.2 Exploration opportunities at Phillips Petroleum

Phillips Petroleum Company has made use of a DA based software package called DISCOVERY. The package provided the Phillips company a means to evaluate risky projects (oil exploration opportunities) in a way that reflected the risk attitudes of their company executives. Walls, Morahan and Dyer (pages 39 - 56) report that Phillips needed to quantify the following issues:

- Evaluate risk not only as a function of the probability distribution of an oil well outcome, but also as a function of the amount of capital exposed to the chance of a loss.

- Trade-off the potential gains versus losses for individual projects (explorations).

- Determine the appropriate level of involvement in other investments for diversification purposes.

Walls, Morahan and Dyer generate profit contribution based on financial premiums, cash considerations, risk preferences, and royalties. A decision tree was used to visualize the decision situation. Once the profit contributions were established, an exponential utility function was employed to determine certainty equivalents, for different levels of risk aversion. Certainty equivalents are defined as the certain value (amount) that a decision maker is willing to accept in lieu of an uncertain gamble [Holloway, 1979:101].

Walls et al. then compared the impact of varying levels of risk aversion to expected value calculations for different levels of diversification involvement. The results indicated that project rankings and their diversification share were quite different when using the Certainty Equivalent basis versus the Expected Value basis. The researchers conclude by

stating that the inclusion of risk attitudes based on exposed capital and diversification preferences can (and did in the Philips case) have a dramatic impact on the preference for project selections [Walls et al., 1995: 39 - 56].

2.4.3 Case Study of Integrated Oil Field Development Strategies

The development strategies for an oil field are quite complex and require an analysis of uncertain variables such as seismic data, performance predictions, hydrogeology, water saturation , and permeability [Stripe, Arisaka, Duandeau, 1993: 155]. To better understand these uncertainties and their effect on the selection of an oil field development strategy, Stripe et al. conducted an analysis for the Hawk Field offshore from Abu Dhabi, Saudi Arabia. In the analysis, optimistic and pessimistic outcomes were evaluated for two different reservoirs. The uncertainties incorporated in the model are shown below:

- Seismic data - especially towards the boundaries of the reservoir
- Water saturation levels
- Soil permeability
- Aquifer support levels
- Soil porosity
- Rock properties throughout the field

A total of 22 different oil recovery methods were investigated. Most methods were slight variations of a standard method. For example, one recovery method studied was to use five-spot water flooding with and without peripheral water injection. Another

was to use pattern gas injection with and without peripheral water injection. An initial screen based on estimated field performance was conducted and the list of 22 removal methods was reduced to 12 full field production scenarios or strategies.

The researchers then conducted an incremental economic analysis as well as a sensitivity analysis of three of the variables. The results were presented as "best strategies" based on cost effectiveness (from the incremental economic analysis) and level of associated risk (from the optimistic and pessimistic assessments). Sensitivities were presented as increases or decreases in incremental discounted income [Stripe et al., 1993: 155 - 167]. Unfortunately, the specific details of the model were not presented in the paper, and thus cannot be presented here. Nonetheless, the use of DA to support technologies for subsurface extraction is clearly demonstrated.

2.5 Decision Analysis and MAUT Applied to Remediation Projects

Remediation projects, because of their multiple and conflicting objectives, have been the source of a number of DA research opportunities. This section outlines the research conducted in the past that makes use of DA and MAUT principles.

2.5.1 Decision Support for CERCLA Investigations

Purucker, Lyon, Stewart, and Nanstad provides an outstanding overview and introduction to DA and its uses in support of CERCLA investigations. The study, issued in September 1994, was prepared for the DOE's Oak Ridge National Laboratory. In it, the authors introduce the concepts and potential applications of DA during a CERCLA process. The goal of the introductory paper was to enlighten DOE personnel about a technique that can be used to supplement the normal Remedial Investigation/Feasibility Study (RI/FS) process and the Data Quality Objective (DQO) process.

The paper outlines the DA process discussed in paragraph 2.2, but uses CERCLA language to describe the steps. For example, the step labeled "identify the potential alternatives" is grouped into a category known as the feasibility study. Purucker et al. discuss objective functions, deterministic and probabilistic analysis as well as subjective probability inputs.

Purucker et al. report the specific application of DA in the area of DOE budgetary decisions. The Environmental Restoration Benefit Assessment Matrix (ERBAM) is used at the Oak Ridge Operations - Environmental Restoration Program to support fiscal budgetary decisions. The ERBAM is a risk based tool that uses prioritization schemes and multiattribute utility analysis to rank order specific environmental restoration projects. It is designed to measure the reduction of risk for each project implemented. The output from the ERBAM is a net benefit score that is based on the objective function shown in (2.2).

$$\Delta \text{Project Benefits} = (W_i S_{ib} L_{ib}) - ((1-W_i) S_{ia} L_{ia}) \tag{2.2}$$

where:

W_i = the weight of the impact - determined through the use of an objectives

hierarchy and the establishment of performance scales

S_{ib} = the severity of the impact before the project in implemented

S_{ia} = the severity of the impact after the project is implemented

L_{ib} = the likelihood of impact occurring before implementation

L_{ia} = the likelihood of impact occurring after implementation

The conclusions drawn from the paper are that DA techniques are being used in the DOE, and they should be used more - especially in the Remedial Investigation/Feasibility Study stages of a remediation project. The example of ERBAM was merely to show that DA techniques are employed by the DOE to make budgetary decisions, and that the same techniques can apply to more technical stages of the remediation process [Purucker, et. al, 1994].

2.5.2 A Simplistic Approach to Remediation Alternatives Selection

The November/December 1995 issue of The National Environmental Journal contained a paper written by Christopher M. Timm that used a simplistic approach to technology selection for a specific remediation project at the DOE facility at Rocky Flats in Colorado. According to Timm, there are four steps necessary to making a quality decision. These steps are: 1) carefully define the decision to be made, 2) generate a list of achievable alternatives, 3) develop meaningful and reliable information, and 4) apply the "logical" tools developed.

The site to be remediated was a series of five wastewater ponds that were used to store and evaporate low level radioactive process wastes (sludge). To satisfy step one, the decision objective was stated as: select "the remediation option that would be the *most realistic* in terms of cost and schedule." In addition to this primary decision objective, other sub-objectives were listed as well. These included items that were specific to regulatory requirements or future operational desires for the site.

A list of achievable alternatives was generated, and reliable and meaningful information obtained for each of them. This information was probabilistically based and contained data such as the probability of a specific technology accomplishing the remediation in a specified time period.

After the information was gathered, the technology alternatives were screened for technical feasibility. Two candidate technology alternatives were eliminated by this process. At this point, nine remained. Next, each alternative was evaluated to see how they met previously set timeline schedules. Once complete, each alternative was evaluated based on: 1) critical elements that could potentially lead to significant changes in either cost or schedule, and 2) life cycle costs and their variability.

Based on these evaluations, specific alternatives (technologies) surfaced as the winners in a specific evaluation criteria. For example, the option labeled partial on-site disposal surfaced as the low cost technology, and the option to rebuild the ponds was the lowest risk (least probable of failing) alternative. The end result of the analysis was a list of technologies that could satisfy the remediation requirements, and were the best in one or more of the evaluation criteria. No attempt was made to consolidate or assign weights

to each criteria. The information was presented to the final decision maker and a remediation technology selection was made [Timm, 1995: 46 - 53].

2.5.3 Decision Support System for DOE Test Pit 9 at INEL

One example of risk based DA research applied to a specific site was completed by Ralston in his 1996 AFIT thesis for the Department of Energy. In this effort, Ralston used the DA process outlined in Section 2.0 to develop a decision support system to aid in the selection of remediation strategies for a test pit at Idaho National Environmental Laboratory (INEL). The DA model developed incorporates risk (probability of a technology failure), time, and cost variables for each candidate remediation technology. Output from the analysis revealed that of the approximately 2,100 possible remediation strategies, less than a dozen were viable alternatives requiring further consideration given the time and cost constraints set by the DOE [Ralston, 1996].

2.5.4 Remedial Alternative Selection at Savannah River

A similar research effort was conducted in a collaborative effort by Evans, Duffield, Massman, Freeze, Stephenson, and Buss. This DA effort focused on a risk based remedial alternative selection at the Savannah River Site. In their research, a DA framework model was built using three other models as drivers: 1) a risk/cost based economic model, 2) a hydrogeological simulation model, and 3) a hydrogeological uncertainty model. The purpose of the research was to demonstrate a method to determine the low cost remediation alternatives and to shed light upon the cost drivers for a waste site at Savannah River. The waste site studied was an unlined earthen basin

disposal facility for low level radioactive effluent material and other chemicals used in separation facilities on site.

The objective function used for the Evans et al. DA framework model is shown in (2.3).

$$\Phi = \sum_{t=0}^{T} [B(t) - C(t) - R(t)] / (1+i)^t \qquad (2.3)$$

where:

B(t) = the annual benefits - measured in dollars

C(t) = the annual costs

R(t) = the annual risks - determined by multiplying a probability by an expected cost of a failure

This is essentially a net present value calculation that captures the three variables described above. In their research, the annual benefits were given the value of zero, and the recommendations were based on the costs and the risks. The costs were subdivided into the following categories:

- Design capital cost

- Design Operations and Maintenance (O&M) Cost

- Total risk capital cost - an account for corrective measures in the event of failure

- Total risk O&M cost - an account for corrective measures in the event of failure

- Regulatory penalty cost

The risk parameter, R(t), is a function of the probability of failure and the cost of a failure in a given year. This equation is shown in (2.4).

$$R(t) = P.(t)C.(t) \qquad (2.4)$$

where:

P.(t) = the probability of failure in year t

C.(t) = the cost of failure in year t

Based on the analysis of six different remedial alternatives, the results indicated that, in general, O&M costs for each of the alternatives was the significant driver. These costs ranged form 54% to 84% of the total cost. Another important result was that, generally, the variable that exhibited the greatest impact on cost was the total volume of groundwater extracted from the site. The risk costs were typically not significant when compared to the O&M costs for this particular site. The specific conclusion drawn was that, at the Savannah River site, the use of extraction wells with surface water disposal of treated effluent was the lowest cost alternative [Evans, Duffield, Massman, Freeze, Stephenson, and Buss, 1994].

2.5.5 Superfund Decision Analysis in the Presence of Uncertainty

Jennings, Mehta, and Mohan describe a DA/MAUT model developed for a Superfund site that pulls together the criteria necessary for assessing a site of this magnitude. In Jennings et al., a modified version of the National Contingency Plan (NCP) Evaluation Criteria (see Appendix B) is used to evaluate alternatives for an old Wisconsin gravel pit that was turned into a waste disposal site. The modified NCP criteria were assigned weights and each was scored using a detailed worksheet that quantifies each criteria element. The results of the composite score for each technology alternative were then used in a normalized utility function. The normalized utility function was then

evaluated using Monte Carlo techniques to simulate the uncertainty surrounding each of the variables and their weights.

Based on an initial alternatives screening using short term and long term effectiveness, as well as implementibiltiy as screens, five remediation alternatives were subjected to the remaining selection process proposed by Jennings et al. The output of the analysis resulted in "rating histograms" for each technology alternative. This provided a visual means to judge each alternative in a stochastic manner. The model also accommodates a good degree of sensitivity analysis that allows for varying the weights, the uncertainty probability distribution functions, and the decision criteria score ranges.

Jennings et al's results indicated that an obvious remediation alternative was not available; however, it was clear that some alternatives were better than others. When one of the parameters was modified (or ranged), the rating histograms shifted. This was particularly evident when ranging the weight assignments. For example, the decision criteria "cost" was quite sensitive to its weight assignment. By ranging this weight (the other weights ranged accordingly because all weights summed to 1.0), the "best" alternative selected would be dramatically different. In other words, the weights of the decision criteria were the most sensitive parameters in their particular model [Jennings et al. 1994: 1132 - 1150].

2.5.6 Modeling the Public as a Stakeholder

To capture all of the concerns related to a remedial action, one must consider the attitudes and objectives of three different stakeholders: 1) the Site Owner (SO), 2) the Regulatory Agency, and 3) the Public [Apostolakis and Bell, 1995: 1021]. To address

these three divergent groups, Apostolakis and Bell developed a methodology to include risk attitudes and values into an influence diagram. The risk attitudes and values are described in terms of objectives. Their study indicated that the SO and the Regulatory Agency are primarily concerned with health risk and cost. The Public, on the other hand, is concerned with the following issues:

- Control: The Public feels threatened by the contamination and would like to somehow control the outcome of any cleanup work.

- Credibility: The Public feels more or less at risk based on the actions of the SO. Thus the SO credibility is a concern of the Public.

- Time to Completion: The Public is concerned about the length of time that a cleanup will take.

- Cost

To demonstrate the implementation of these concerns and objectives into a remedial action decision situation, an Influence Diagram was constructed based on a theoretical site that required a selection between two different pump and treat technologies. The Apostolakis and Bell influence diagram is found in Figure 2.4.
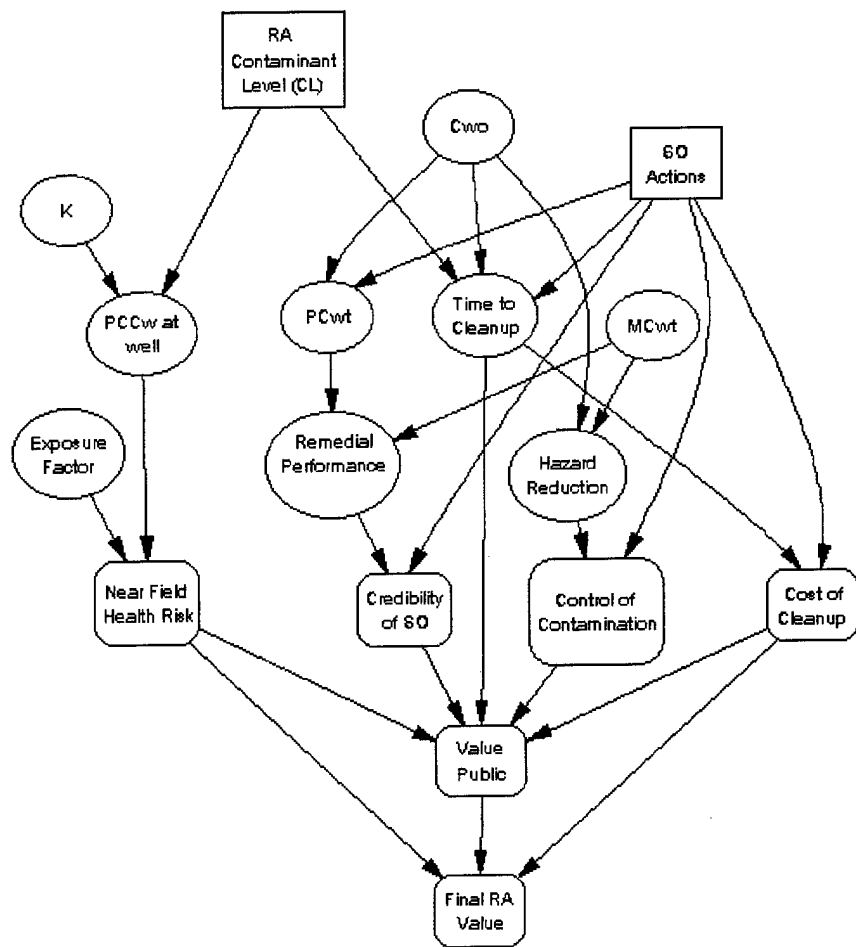
Figure 2.4 Influence Diagram Developed by Apostolakis and Bell (page 1024)

An explanation of the nodes shown in Figure 2.4 are discussed in Table 2.1.

Table 2.1 Node Explanation for Figure 2.4

Node Identifier	Node Type	Description
RA Contaminant Level (CL)	Decision	The decision here is between MCL (Maximum Contaminant Level) and ACL (Alternate Contaminant Level). It determines the amount of contaminant left after cleanup.
SO Action	Decision	This decision node represents the technology decision made by the SO between the two different pump and treat technologies.
Cwo	Chance	The initial concentration at the site.
K	Chance	Hydraulic Conductivity of the hydrogeology.
PCCw at Well	Chance	Predicted Contaminant Concentration in the water.
Pcwt	Chance	Predicted Concentration at time t. Used to gauge remediation progress.
Time to Cleanup	Chance	Time required to cleanup the site to the level decided upon by the SO.
Mcwt	Chance	Measured concentration of contaminant in the water at a given time.
Exposure Factor	Chance	Represents the exposure assessment step in the health risk evaluation. It is an estimate of the chemical uptake from potential pathways.
Remedial Performance	Chance	Used to reflect the SO's ability to achieve the established goals.
Hazard Reduction	Chance	Used to measure progress by comparing the original source concentration to the current concentration after some time t. (i.e. (Cwo - MCwt)/Cwo x 100).
Near Field Health risk	Calculation or Value	Represents the risk to human health after cleanup is completed to the SO specified level.
Credibility of SO	Calculation or Value	Represents the efforts of the SO and is influenced by the remedial performance and the communication of risk to the public.
Control of Contamination	Calculation or Value	Represents the SO's control over the hazardous contaminant. Influenced by the SO actions and the hazard reduction.
Cost of Cleanup	Calculation or Value	Total estimated present worth cost incurred by the SO to cleanup the contaminant to the level agreed upon in the decision node Level.
Value Public	Calculation or Value	Final utility value of remediation technology as perceived from the public.
Final RA Value	Calculation or Value	Final utility value from the Remediation Authority perspective. Takes into account the public utility.

Unfortunately, Apostolakis and Bell do not include a real example application of their work. Nonetheless, it is a useful representation of modeling stakeholder preferences and their attitudes towards risk [Apostolakis et al., 1995; 1021 - 1026].

A number of attempts have been made to implement DA and MAUT concepts into the decision making required to remove substances (either contaminants or fuels) from the subsurface. However, there is no known specific application of remediating a site contaminated with DNAPL pollutants. As stated in Chapter 1, DNAPLs present a unique challenge because of their properties and widespread use. The next chapter uses the ideas discussed in this literature review to build two models for selecting DNAPL remediation strategies that provide the greatest utility to the decision maker.

III. Methodology

3.1 Introduction

Based on the literature review and the available documentation, a two-phased approach using multi-attribute decision theory as a foundation was utilized in this study. The first phase constructs a MAUT model that was used to screen the candidate technology trains. The second phase uses the results of the first phase to build a model to conduct in-depth risk analysis of the most favorable strategies. Both phases and their results can be used by the DOE to complement other efforts that are required during the Feasibility Study phase of the C-400 remediation project.

This section will cover the following areas:

- DOE requirements and model focus discussion

- WAG6 and C-400 site characteristics

- The Screening (Phase 1) model development and dominance discussion

- The Probabilistic (Phase 2) model development

Due to the iterative nature of modeling complex decision situations, the requirements, technology candidates, and models developed were continually modified and updated. The major updates and changes have been captured and are discussed in Appendix G.

3.2 Focusing the Model

At the outset of this effort, the DOE expressed interest in the development of a generic decision model that could be used at any of a number of DNAPL sites. The general desire was to build a modeling framework that uses hydrogeological

characteristics, cost, time, and performance data for individual technologies as inputs and to output technology train selections that meet certain threshold limits. At the time, the cost limit was stated as a cost less than $50 million for the total remediation, with no more than $10 million spent per year during the planning horizon. The planning horizon time constraint was 6 years. There are no general relationships between every possible combination of cost, time, and performance for every potential hydrogeologic characteristic, without prior knowledge of the site specific characteristics. Because of this, a more site specific, tailored approach was used. The framework developed, however, can be used at other sites, provided it is populated with appropriate data and relations.

Tightening the modeling focus, two decision models were developed for the C-400 site. The models are explained in Section 3.4. The requirements outlined by the DOE evolved as the project progressed. The final set of requirements are shown below:

- Build a decision model or models that incorporate life cycle cost, time, and performance data

- The models are to use cost, time, and performance data that has been generated by a life cycle cost model owned and operated by Mountain State Engineering (MSE)

- The decision models are to be used to select the best technology trains by optimizing any one or more of the three attributes (cost, time, performance)

- Conduct sensitivity analysis on the variables that exhibit the greatest degree of influence

- Include uncertainty values where appropriate

It is this final set of requirements that the models were built against.

3.3 WAG6 and C-400 site characteristics

This section provides insight into the site characteristics for the WAG6, C-400 site and how they related to the models.

The Paducah Gaseous Diffusion Plant (PGDP), located in Paducah, Kentucky, is a uranium enrichment facility owned by the DOE and operated under contract by Lockheed-Martin Energy Systems. In May, 1994 the entire plant was placed on the National Priorities List. To address the contamination issues, a Remedial Investigation/Feasibility Study process was begun. During the initial phases of this process, the WAG6 site was identified and separated as an individual remediation project. The WAG6 site is composed of 5 individual Solid Waste Management Units (SWMUs). Four of the five SWMUs are located in an area near the C-400 building. The fifth SWMU is a transfer line located in close proximity to the others. These 5 SWMUs make up the primary contaminant release points.

The two contaminants of concern at the C-400 site are Trichloroethylene (TCE) and Technetium 99 (^{99}Tc). Of these two, the primary contaminant of concern in this study is TCE. During the course of this study, two estimates of TCE spill volume were provided by different DOE contacts. One estimate ranged from 2,000 - 50,000 gallons. The other estimate ranged from 100,000 - 500,000 gallons. Because of the lack of specific data and the uncertainty surrounding the spill volume, the experts at the DOE chose to base the analysis on a conservative volume estimate of 7,500 gallons. The spill volume source of 7,500 gallons is shown schematically in Figure 3.1. (See Appendix J for more information regarding the spill volume.)
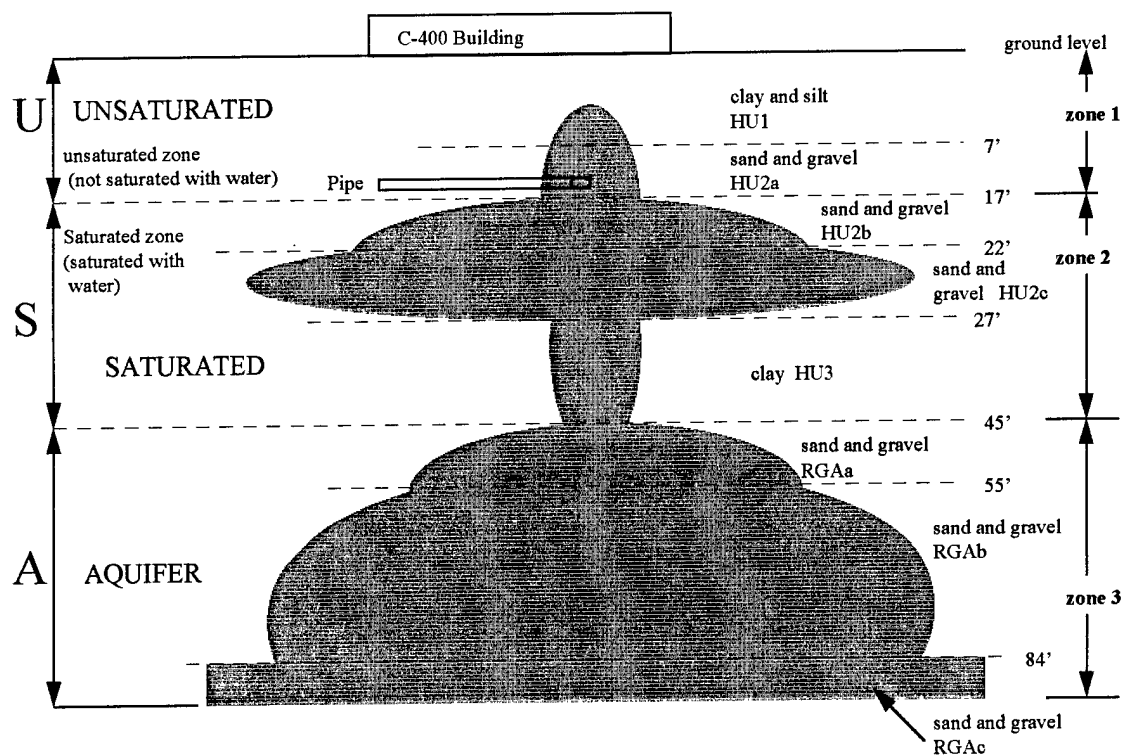
Figure 3.1 Idealized Schematic of Contaminant Source

From Figure 3.1, it can be seen that there are 8 different hydrogeologic units

(HU1, HU2a, HU2b, and so forth). Each hydrogeological unit is delimited in Figure 3.1

by a horizontal dashed line. Each of these units is composed of different hydrogeological

characteristics that promote nonhomogeneous contaminant migrations. Based on

discussions with the key decision makers, it was decided to break the 8 zones into 3

operational zones: 1) Unsaturated Zone (U), 2) Saturated Zone (S), and 3) Aquifer (A).

This simplification was based on the fact that it is unlikely that more than 3 different

contractors, treating different zones, would work on the same site simultaneously. The

logistics and coordination required to maintain more than 3 contractors was considered to

be untenable. The use of this simplification treats nonhomogeneous subsurfaces in a

3-4

homogeneous manner. Because of this, additional uncertainty was introduced into the problem. Nonetheless, while this simplification aggregates some of the detailed hydrogeological characteristics, it was felt by the decision makers and the research team to be a better reflection of the operational aspects of remediation projects that had been done in the past.

3.4 Model Development

Due to the iterative nature of model building, four different prototype models were developed to varying degrees of maturity. Each of the models served the purpose of assisting in the screening process. Through the use of these models, the number of potential technology trains was reduced from approximately 16.8 million to 58. The iterations required to reach the requisite models are found in Appendix G. This section contains a complete description of the requisite screening model (phase 1) and the probabilistic model (phase 2).

3.4.1 Screening Model Development (Phase 1)

The first model was developed as a screening tool to identify the most promising trains. The decision situation is separated into three distinct areas: (1) Unsaturated, Saturated, and Aquifer (USA) - a strategy that is characterized by using trains that use one technology pair to treat all three zones, (2) Unsaturated/Saturated and Aquifer (U/S & A) - a strategy that is characterized by using trains that use one technology pair to remediate the unsaturated zone and the saturated zone, and another technology pair to remediate the aquifer, (3) Unsaturated and Saturated/Aquifer (U & S/A) - a strategy that is

characterized by using trains that use one technology pair to remediate the unsaturated zone, and another technology pair to remediate the saturated zone and the aquifer. Figure 3.2 shows the influence diagram of the model. Each area represents a different strategy that is based on realistic trains developed through the iterative modeling process. The trains are formed by combining specific technologies that are used collectively to remediate all 3 zones

The first strategy type, the USA strategies, are shown in Table 3.2 They are designated as USA trains because of their ability to treat all of the zones at the C-400 site. The other two strategy types are: 1) U/S & A (Unsaturated, Saturated & Aquifer) and 2) U & S/A (Unsaturated & Saturated, Aquifer). The U/S & A strategy is composed of 48 trains that are so designated because of their ability to treat the C-400 site using the same technology pair for the unsaturated zone and the saturated zone, but require a different technology pair for the aquifer. These trains are shown in Table 3.3. The U & S/A strategy is composed of 8 trains, and is so designated because of their use of the same technology pair for the saturated zone and the aquifer, but a different technology pair for the unsaturated zone. These trains are shown in Table 3.4. A key for the acronyms used in these three tables is presented in Table 3.5.

USA
Strategies

U/S & A
Strategies

S/A & U
Strategies
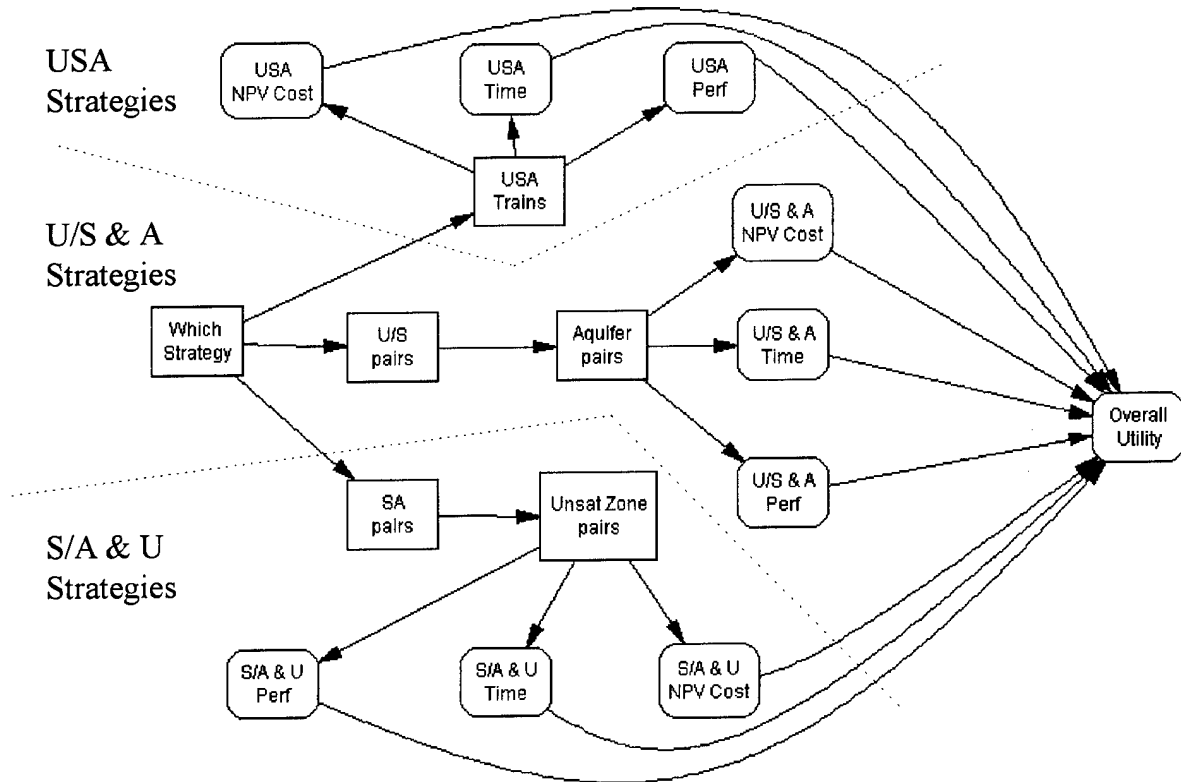
Figure 3.2 Screening Model Influence Diagram

An explanation of each of the nodes shown in Figure 3.2 is found in Table 3.1.

Table 3.1 Node Explanation for Figure 3.2

Node Identifier	Node Type	Description
Which overall strategy	Decision	The decision here is between USA, U/S &A, and U & S/A strategy types
USA Trains	Decision	The decision is between 2 USA Trains
USA NPV Cost	Value	Contains cost data for USA Trains
USA Time	Value	Contains time data for USA Trains
USA Perf	Value	Contains performance data for USA Trains
U/S pairs	Decision	The decision is to select 1 of 4 technology pairs to be used in the unsaturated and saturated zones
Aquifer pairs	Decision	The decision is to select 1 of 12 technology pairs to be used in the aquifer. It will accompany the U/S pair.
U/S & A NPV Cost	Value	Contains cost data for U/S & A Trains
U/S & A Time	Value	Contains time data for U/S & A Trains
U/S & A Perf	Value	Contains performance data for U/S & A Trains
S/A pairs	Decision	The decision is to select 1 of 2 technology pairs for the saturated zone and the aquifer
Unsat Zone pairs	Decision	The decision is to select 1 of 4 technology pairs to be used in the unsaturated zone. It will accompany the S/A pair.
U & S/A NPV Cost	Value	Contains cost data for U & S/A Trains
U & S/A Time	Value	Contains time data for U & S/A Trains
U & S/A Perf	Value	Contains performance data for U & S/A Trains
Overall Utility	Value	Calculates the utility values for each Trains

A technology pair is the combination of a primary technology and an accompaniment technology. For example, one technology pair shown in Table 3.2 is DUS, or Dynamic Underground Stripping combined with Bio (Biological Remediation). In this example, DUS is the primary technology, and Bio is the technology accompaniment. Together they make up a technology pair (and in this case a train too). The other technology pair shown in Table 3.2 is DUS and P&T, or Pump and Treat. A complete description of the individual technologies is found in Appendix D.

Table 3.2 USA Trains

for all 3 zones		Number of Combinations
DUS	Bio P&T	2

total = 2

Table 3.3 U/S & A (Same Technology pair for the Unsaturated and Saturated Zone, Different Technology for Aquifer)

for unsaturated & saturated zones		for aquifer	Number of Combinations
two phase	none RF 6 phase	choose 1 of 12	3 x 12 = 36
LASAGNA	none	choose 1 of 12	1 x12 = 12

total = 48

1 of 12 choice list
Oxidation & Bio
Oxidation & none
Cosolvent & Bio
Cosolvent & none
Surfactant & Bio
Surfactant & none
UVB & Bio
UVB & None
P&T & Bio
P&T & None
PTZ & Bio
PTZ & None

Table 3.4 U & S/A (One Technology Pair for the Unsaturated Zone, Different Technology Pair for the Saturated Zone and Aquifer)

for unsaturated zone		for saturated & aquifer zones		Number of Combinations
SVE	none		Bio	4
2 phase	none RF 6 phase	P & T	none	4

total = 8

Table 3.5 Key for Tables 3.2, 3.3, and 3.4

Abbreviation	Complete Name
6 phase	Heating technology that uses a 6 point electrode scheme
Bio	Biological Treatment
Cosolvent	Cosolvent Flushing
DUS	Dynamic Underground Stripping
LASAGNA™	Trade name for specific heating technology
None	None - i.e. no accompaniment
Oxidation	Makes use of an oxidant solution such as H_2O_2 to degrade contaminants
P&T	Pump and Treat
PTZ	Permeable Treatment Zone
RF	Radio Frequency Heating
Surfactant	Surface Active Agent Flushing
SVE	Soil Vapor Extraction
Two Phase	Two Phase Heating
UVB	UVB

The screening model shown in Figure 3.2 illustrates the decision situation, but does not show the full compliment of value nodes contained in the DPL model. Absent are the value nodes that are imported from an Excel spreadsheet. Because the DPL model is linked to an Excel spreadsheet, 232 value nodes (1 for each NPV cost, time, performance, and O&M cost value for each train) are necessary to drive the DPL model. The complete DPL model listing is contained in Appendix H.

The objective function contained in the node "Overall Utility" is composed of weights and utility functions derived from, and refined with, the Decision Makers (DM's) during a series of meetings. The utility functions and weights were derived using two methods. A probability wheel and an Analytical Hierarchy Process technique were used independently to insure accurate results. The probability wheel makes use of an "eye-ball" graphic technique that requires a direct assessment of each attributes weight. The

Analytical Hierarchy technique involves the use of specific trade-offs between each

attribute. Both techniques yielded similar results. The objective function is shown in

(3.1). The utility function pieces are shown in Figure 3.3

$$\text{Overall Utility} = 0.44*(\text{cost utility}) + 0.12*(\text{time utility}) + 0.44*(\text{performance utility}) \qquad (3.1)$$
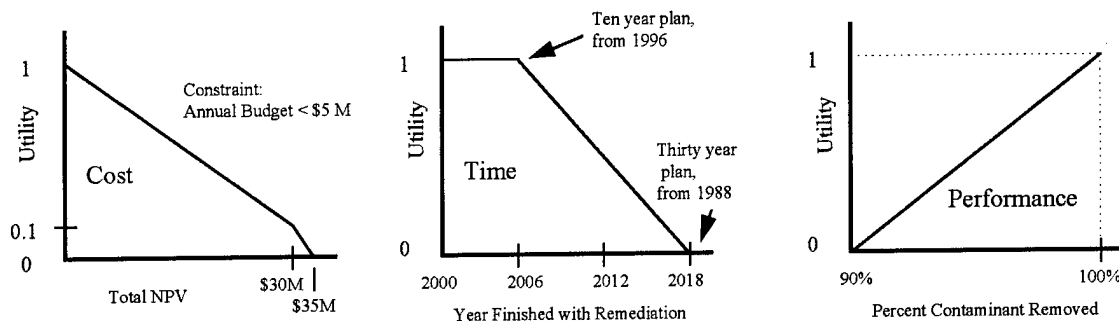
Figure 3.3 Utility Functions

A complete discussion of the results and conclusion derived from this model are found in

Section 4.2.

3.4.2 Dominance

As part of the screening process, an Excel spreadsheet was built to determine the

trains that were not dominated by other trains. For this study, a train is said to be "strictly

dominated" if each attribute value is less than or equal to that of another train. For

example, if train 3 had an NPV cost of $1.4 million, a time value of 3.5 years, and a

performance level of 94%, and train number 144 had an NPV value of $2.2 million, a time

value of 7.3 years, and a performance level of 82%, then train 144 is said to be dominated by train 3. Since train 3 is superior to 144 in all three of the criteria, there would be no need to consider train 144 further if the data used for comparison were reliable. A complete discussion of the results of the dominance analysis is presented in Section 4.2.

3.4.3 Probabilistic Model Development (Phase 2)

The probabilistic model was developed to gain in-depth insight into the most promising candidate trains that were acceptable after the analysis based on the screening model. See Section 4.2 for an in-depth discussion of the results of the screening model. Figure 3.4 shows the influence diagram of the probabilistic model.
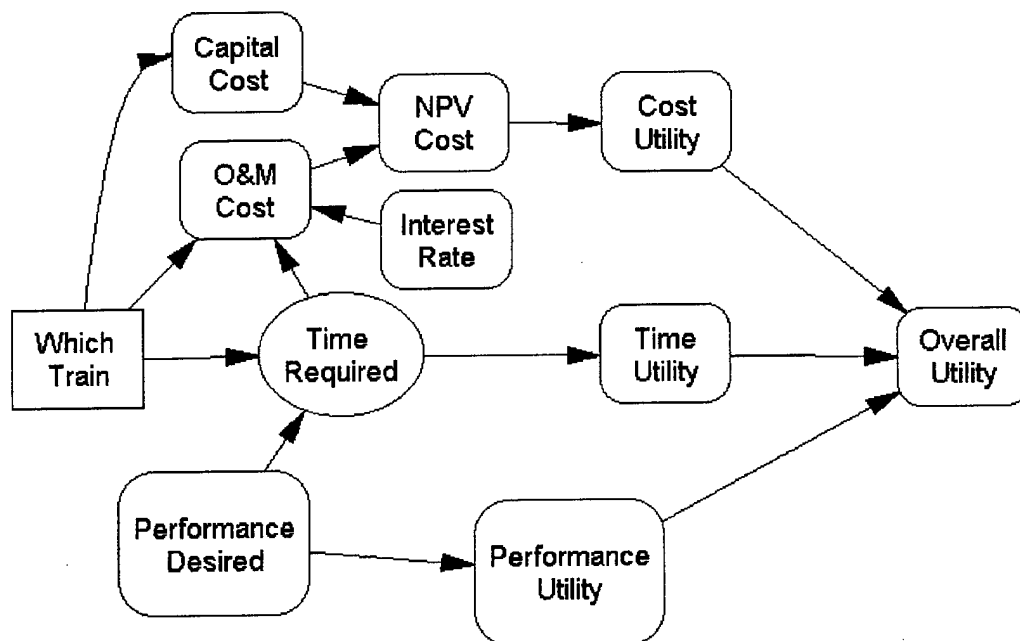
Figure 3.4 Probabilistic Model (Phase 2) Influence Diagram

An explanation of each of the nodes shown in Figure 3.4 is found below in Table 3.6.

Table 3.6 Node Explanation for Figure 3.4

Node Identifier	Node Type	Description
Which Train	Decision	Contains a list of the seven trains chosen for further analysis. They are no. 3, 4, 94, 119, 135, 148, and 156 (156 is the baseline).
Capital Cost	Value	Contains values for the capital cost of each train. This data was derived from the data found in Appendix F.
O&M Cost	Value	Contains values for the operating and maintenance cost of each train. This data was derived from the data found in Appendix F.
NPV Cost	Value	Combines the Capital Cost and the O&M Cost. This node does not discount the O&M costs.
Cost Utility	Value	Converts NPV cost into a utility score using the functions found in Figure 3.3
Time Required	Uncertainty	Uses the data found in Appendix I to calculate the time required for a given performance level
Time Utility	Value	Converts time used into a utility score using the functions found in Figure 3.3
Interest Rate	Value	Interest rate value used to compute the present value of a stream of operating costs - nominal value: 2.5%
Performance Desired	Value	A single value that can be changed to analyze train costs and time levels for different performance levels
Performance Utility	Value	Converts the performance attained into a utility score using the functions found in Figure 3.3
Overall Utility	Value	Combines the individual utility scores into a combined score using (3.1)

In addition to the nodes discussed above, there are 8 other value nodes that are used to conduct sensitivity analysis. These nodes are explained in Table 3.7.

Table 3.7 Node Explanation for Remaining Nodes

Node Identifier	Node Type	Description
Performance Utility Factor	Value	Used to conduct sensitivity analysis on the performance utility function
Cost Utility Factor	Value	Used to conduct sensitivity analysis on the cost utility function
import_cost_wt	Value	Used to conduct sensitivity analysis on the cost weight factor found in (3.1). This node is imported from an Excel spreadsheet
import_time_wt	Value	Used to conduct sensitivity analysis on the time weight factor found in (3.1). This node is imported from an Excel spreadsheet
import_perf_wt	Value	Used to conduct sensitivity analysis on the performance weight factor found in (3.1). This node is imported from an Excel spreadsheet
export_cost_wt	Value	Used to conduct sensitivity analysis on the cost weight factor found in (3.1). This node is imported from an Excel spreadsheet
export_time_wt	Value	Used to conduct sensitivity analysis on the time weight factor found in (3.1). This node is imported from an Excel spreadsheet
export_perf_wt	Value	Used to conduct sensitivity analysis on the performance weight factor found in (3.1). This node is imported from an Excel spreadsheet

From Figure 3.4, it is seen that one decision node drives the model. This decision node contains the most promising trains that have been selected by the DMs for further evaluation.

For this in-depth analysis, and to gain better insight into the annual costs, the cost figures need to be separated into Capital and Operating and Maintenance (O&M). This is consistent with the work done by Evans et al. In their work, Capital Costs, and Design Operations and Maintenance costs were broken out separately. Like the screening model, these costs are converted into utilities using the utility profiles presented in Figure 3.3.

Note that the Performance Desired node is not dependent on the train decision. The desired performance was modeled as an input variable to determine the expected value of cost and time that would be realized as a result of setting a specific performance goal. During the analysis, the Performance Desired variable was fixed for a given scenario. It was then manually changed to determine the expected value of total cost and time required for each train. For instance, by setting the Performance Desired value to say 90%, the DM would be able to determine the expected value of total cost and the time required for each train at the 90% performance level. This could be compared to the expected value of cost, and time required for 95% and so on. The performance value is also converted into a utility number using the utility functions shown in Figure 3.3.

The Time Required node is an Uncertainty node that represents the uncertainty surrounding the time that is expected to be required for a given performance level. The data was derived during a technical discussion with DOE technology experts. During the discussion, three specific performance levels were set to represent a low, medium, and high performance levels that might be realized for each train. Then a low, expected, and high time value was assigned to each performance level for each train. The data obtained during this discussion and plots of this data are presented in Appendix I.

To make the best use of the data that was obtained (see Appendix I), the Extended Pearson Tukey Method was used. This method was used because of its historical ability to represent a multitude of distributions with only low, medium, and high data points. The method approximates continuous distributions by assigning the .05 and the .95 fractiles a probability of 0.185. The median value is assigned a probability of 0.63 [Clemen, 1996:

278]. Like the other two attributes, the time required is converted into a utility, according to the relationship given in Figure 3.3.

To maintain the maximum amount of flexibility, the model was built so that any number of scenarios may be run to maximize or minimize any of the values listed below for a given Desired Performance value:

- Capital Cost
- O&M Cost
- Total NPV Cost
- Cost Utility
- Time Utility
- Performance Utility
- Overall Utility

By keeping track of each of these values during scenario runs, comparisons and specific insights were gained. These insights and comparisons are presented in Section 4.3 The complete DPL model code listing is contained in Appendix H.

This general methodology, when populated with site specific data and relations, can be used to analyze other DNAPL sites.

IV. Results and Analysis

4.1 Introduction

Analysis was conducted based on the methodology and models described in Chapter 3. The results of the analysis are presented here. Before presenting the results though, it is important to keep in mind the purpose and objectives of this research. As stated in Chapter 1, a decision support system which incorporates operational risk for assessing remediation technology strategies at DNAPL sites was to be built. This decision support system, tailored for the C-400 site, consists of two models that were developed and used as 1) a screening model, and 2) a probabilistic model which focuses on the "best" technology trains. Section 4.2 is devoted to the first phase of this analysis (screening), and Section 4.3 is devoted to the probabilistic phase. Both models provide insight into the cost, time, and performance characteristics of the technology train candidates. The insights and results of the analysis are used to justify the screening of technology trains. It is this screening process and the insight gained from the results that are the major contributions of this research. While the analysis is current for the available data and assumptions, care should be exercised in drawing any final conclusions from the analysis while questions of the spill volume remain open. The analysis does, however, illustrate the type of information that can be made available to the decision makers from this project.

To fully understand the results and analysis, it is necessary to review the assumptions used. These assumptions have been discussed throughout this document, especially in Chapter 3. The assumptions used are repeated below:

- Cost, Time, and Performance Data - The data used as a foundation for both models (especially the screening model) was provided by Mountain State Engineering (MSE). They have built a comprehensive life cycle cost (LCC) model that is capable of amassing a large volume of cost, time, and performance data, compiling it, and providing output that can be used for analysis efforts such as this one. The screening of each train is based on the final data set provided by MSE on 15 Jan 97. See Appendix F for a complete listing of the data.

- Spill Volume: - The data set provided by MSE on 15 Jan 97 was based on point estimates for a spill volume of 7,500 gallons. See Appendix J for information about the uncertainty of the actual spill volume.

- Probabilistic Performance and Time Data - The probabilistic model (phase 2) uses performance and time relationships that were gathered on 23 Jan 97 during a meeting with DOE technical experts. The modeling of this relationship was discussed in Section 3.4.3. The data is found in Appendix I.

- Cost Penalty - A cost penalty was assigned to trains that did not meet a 90% performance level. The cost penalty was based on an additional technology application of pump and treat. If a technology train did not meet the 90% threshold, it was penalized by increasing its capital and operating costs by assuming that a pump and treat system would be added to the train.

- Cost Constraint - The Decision Makers set a cost constraint of $5 million per year for O&M costs.

- Interest Rate - The Probabilistic Model used a nominal interest rate of 2.5% to discount the O&M costs. A complete analysis of the sensitivity of this parameter indicated that the decision policies are not sensitive to this choice of interest rate.

The remainder of this chapter is broken into the following major sub-sections:

- Section 4.2 - Results and Analysis of Screening Model (Phase 1)
- Section 4.3 - Results and Analysis of Probabilistic Model (Phase 2)

4.2 Results and Analysis of Screening (Phase 1) Model

Because of the deterministic nature of the data used in the screening process, a preliminary deterministic based screening was performed. The purpose of the modeling effort was to screen technology trains from an initial candidate list of 58 to a smaller set that would warrant more detailed analysis. Table 4.1 shows the ranking of the trains when the objective function (3.1) is driven by a single attribute, with the contributions of the other attributes ignored. The reason for this initial ranking is to determine which trains exhibited the "best" values in each of the attribute categories. Column 1 of Table 4.1 gives the ranking with a cost weight of 1.0; the other weights (for time and performance) are set at 0. Column 2 uses a time weight of 1.0; the other weights (for cost and performance) are set to 0. Column 3 of Table 4.1 gives the ranking with a performance weight of 1.0; the other attribute weights (cost and time) are set to 0.

Table 4.1 Trains Ranked Individually by Cost, Time, and Performance

Rank	Cost weight = 1	Time weight = 1	Performance weight = 1		Rank	Cost weight = 1	Time weight = 1	Performance weight = 1
1	3	4	142		30	139	71	132
2	142	148	136		31	100	156	140
3	136	132	148		32	84	128	4
4	144	100	135		33	127	160	95
5	148	84	147		34	155	96	79
6	4	151	141		35	95	80	89
7	143	126	94		36	79	124	73
8	156	94	78		37	87	122	123
9	135	78	88		38	71	92	138
10	147	125	72		39	99	76	92
11	141	127	139		40	83	90	76
12	151	155	87		41	93	74	127
13	126	119	71		42	77	99	121
14	120	3	99		43	137	83	144
15	128	131	83		44	138	120	90
16	160	142	93		45	153	139	74
17	132	143	77		46	152	137	124
18	140	141	100		47	124	144	153
19	94	135	84		48	123	140	152
20	78	147	119		49	122	138	96
21	119	123	125		50	91	136	80
22	131	121	143		51	75	91	122
23	125	95	126		52	92	75	128
24	88	79	120		53	76	89	155
25	72	93	131		54	121	73	151
26	96	77	137		55	89	158	158
27	158	153	3		56	73	157	157
28	80	152	91		57	90	88	160
29	157	87	75		58	74	72	156

From Table 4.1, it is seen that the top 5 trains ranked by cost are 3, 142, 136, 144, and 148. The top 5 trains ranked by time are 4, 148, 132, 100, and 84. For performance, the top 5 trains are: 142, 136, 148, 135, and 147.

It is interesting to note at this point that, based on the data available and the model assumptions, both of the USA trains (3 and 4) are in the top ranks. They both use Dynamic Underground Stripping (DUS) as their primary technology. Train 3 couples DUS with biological treatment, and train 4 couples DUS with pump and treat. The others (84, 100, 132, 135, 136, 142, 144, 147, and 148) are U/S & A trains.

Another point of interest is that of these top U/S & A trains, 3 of them (84, 100, 132) use two phase vacuum extraction as the primary technology in the unsaturated and

saturated zone. The other 6 (135, 136, 142, 144, 147, 148) use LASAGNA as the

primary technology. In addition, note that each of the three two phase vacuum extraction

trains use a permeable treatment zone (PTZ) technology for the aquifer. Conversely, each

of the 6 LASAGNA trains uses a different technology pair to treat the aquifer. For

example, train 135 uses LASAGNA for the unsaturated and saturated zone, and then uses

oxidation and biological for the aquifer. Train 144 uses LASAGNA for the unsaturated

and saturated zone as well, but uses pump and treat for the aquifer.

If one were to stop the analysis at this point, the results thus far suggest that the

DUS (both USA trains), and LASAGNA trains as well as the trains that couple two phase

vacuum extraction with PTZ should be analyzed further.

Since the decision makers are concerned with the mix of benefits from these

attributes, the trains were ranked by overall utility. Table 4.2 shows this ranking when the

objective function is given by (3.1) - i.e. the weights for cost, time, and performance are

0.44, 0.12, and 0.44 respectively. From this ranking, and the use of Appendix F, it is seen

that the top 6 trains use LASAGNA to remediate the unsaturated and saturated zone. This

is another strong indication that, based on the available data and assumptions, the

LASAGNA trains are good candidates for further evaluation. The top six trains were

chosen as a breaking point because of the break exhibited in the overall utility score. The

overall utility score drops from 0.913 on the sixth ranked train to 0.899 on the seventh.

Table 4.2 Trains Ranked by Overall Utility

Rank	Train Number	Overall Utility		Rank	Train Number	Overall Utility
1	142	0.936		30	132	0.597
2	148	0.927		31	140	0.538
3	135	0.917		32	4	0.526
4	147	0.915		33	156	0.522
5	141	0.915		34	144	0.519
6	136	0.913		35	151	0.518
7	94	0.899		36	128	0.510
8	78	0.898		37	160	0.510
9	139	0.888		38	96	0.495
10	87	0.880		39	80	0.495
11	71	0.880		40	127	0.489
12	93	0.878		41	155	0.489
13	77	0.878		42	95	0.487
14	99	0.877		43	79	0.486
15	83	0.876		44	153	0.475
16	88	0.863		45	152	0.474
17	72	0.862		46	124	0.472
18	100	0.802		47	158	0.469
19	84	0.802		48	157	0.468
20	119	0.763		49	138	0.467
21	125	0.761		50	123	0.460
22	143	0.744		51	122	0.458
23	126	0.737		52	92	0.457
24	120	0.728		53	76	0.457
25	3	0.717		54	121	0.446
26	131	0.717		55	90	0.443
27	137	0.697		56	74	0.443
28	91	0.617		57	89	0.427
29	75	0.617		58	73	0.426

Train 144 (one of the top ranked LASAGNA trains discussed previously) ranked no. 34 in overall utility because it requires 7.2 years and performs at a low level of 82%. Train 144's low performance level is driven by the use of a pump and treat system for the aquifer, whereas the other LASAGNA trains use technologies for the aquifer that have been scored higher on performance.

It is interesting to note at this point, that the two USA trains (3 and 4) ranked relatively low in overall utility. Train 3 ranked no. 25 and train 4 ranked 32. The reason for this is their relatively low performance level. Despite their low cost (train 3 ranked no. 1 for low cost) and their short time horizon (train 4 ranked no. 1 for time), their overall

utility score was lower because of their predicted lackluster performance. Train 3 is expected to attain a maximum performance level of 94%, and train 4 a 90% level. For a complete listing and description of these trains, see Appendices D and F.

To understand the dominance relationships between Net Present Value (NPV) cost, time, and performance, scatter plots were generated using the raw data found in Appendix F. Scatter plots of cost versus time, cost versus performance, and time versus performance were generated. They are shown in the Figures 4.1, 4.2, and 4.3. The dotted line represents the boundary of "best" values, the efficient frontier.
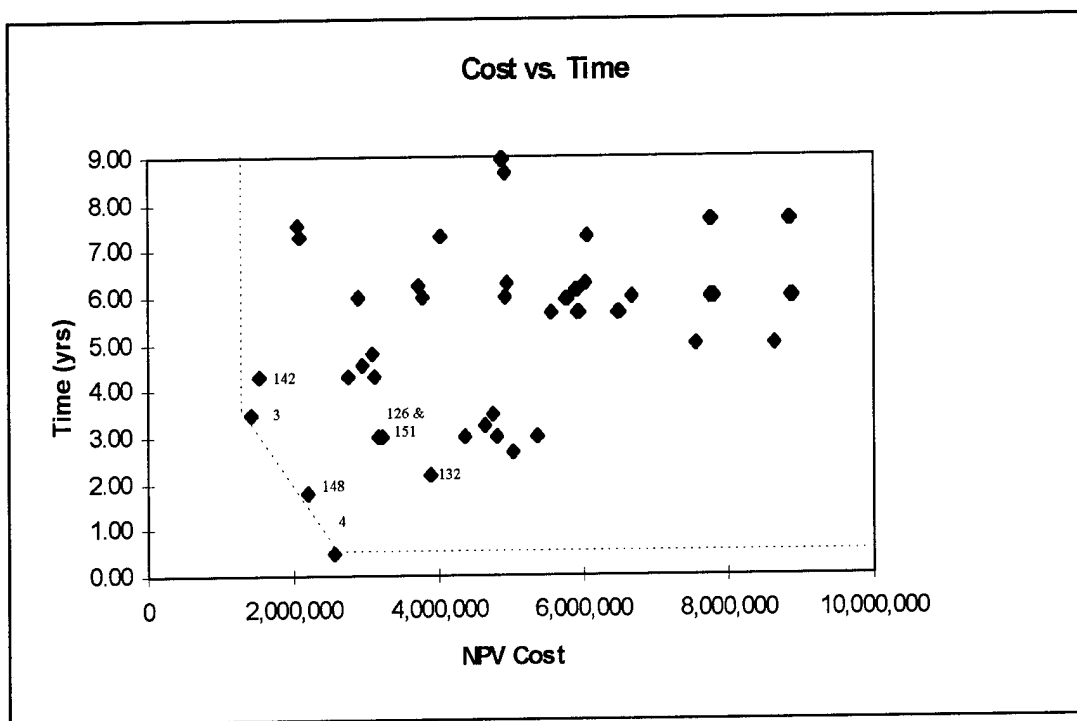
Figure 4.1 NPV Cost vs. Time Scatter Plot
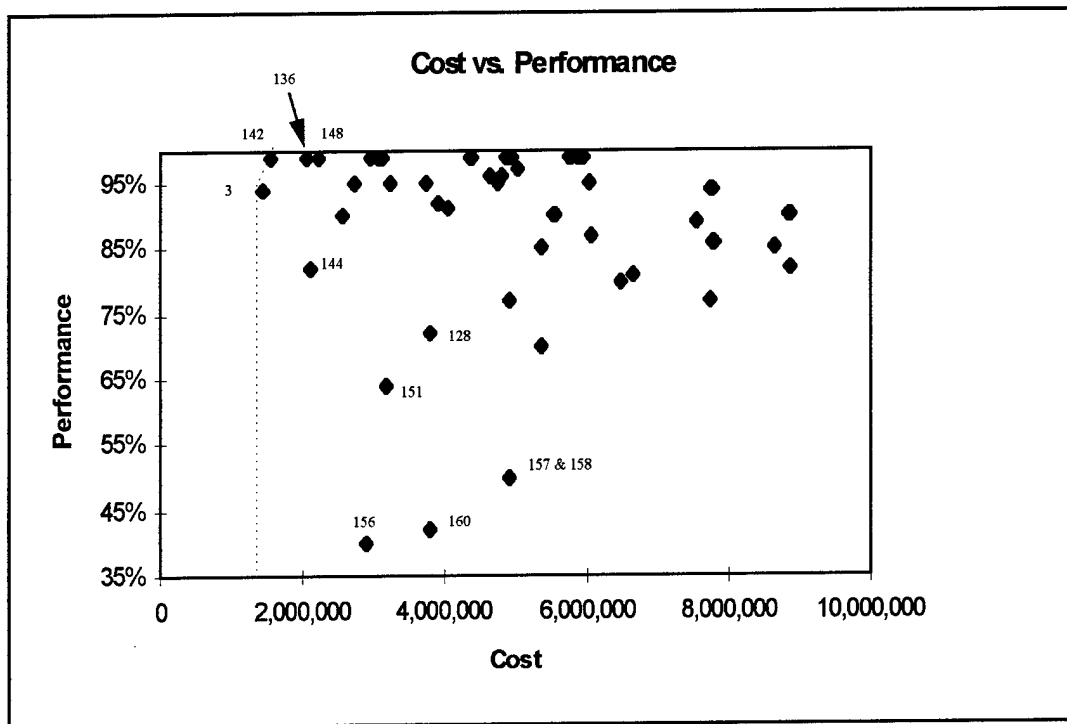
Figure 4.2 NPV Cost vs. Performance Scatter Plot
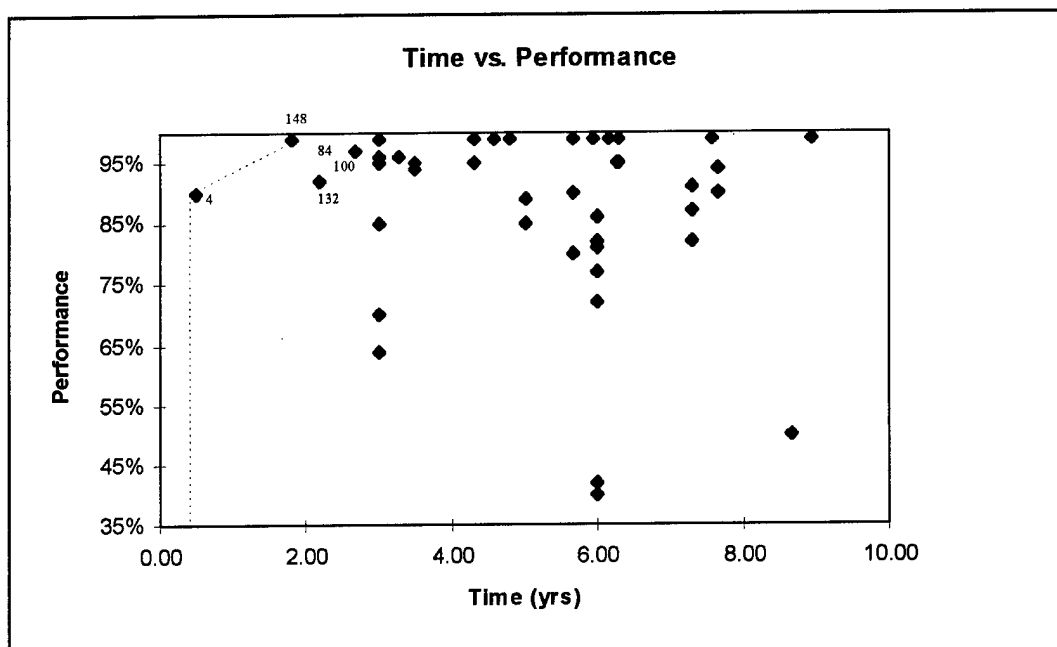
Figure 4.3 Time vs. Performance Scatter Plot

From Figures 4.1, 4.2, and 4.3, it can be seen that trains 3, 4, 142, and 148 lie on the boundary or frontier of at least one of the plots. This indicates that each of these trains are not dominated by the other trains. This is a very important finding, because if we have high confidence in the data used to generate the plots, all of the dominated trains (i.e. all trains except 3, 4, 142, and 148) could be discarded from further evaluation. Another way to visualize dominance is through the use of a radar chart.
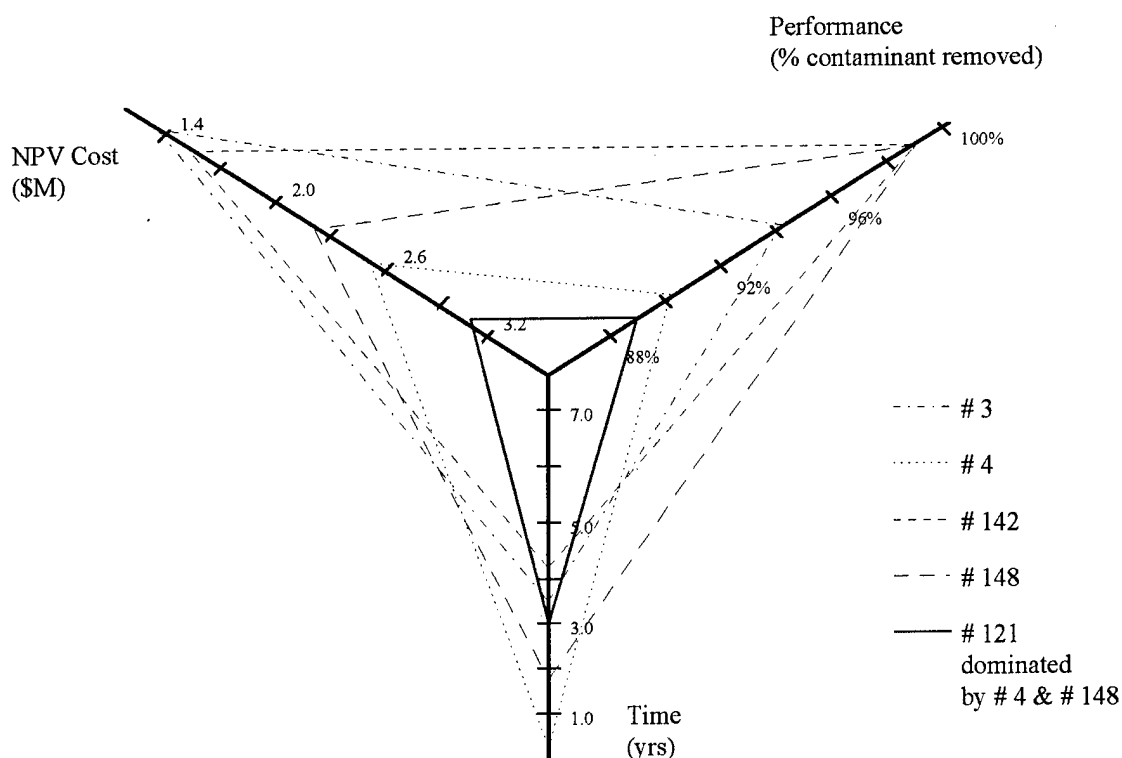
Figure 4.4 Radar Chart showing Dominance of Trains

Figure 4.4 is a graphical representation showing the nondominated set of trains and one dominated train. The dominated train is added to aid in understanding the figure. When viewing a radar chart, one looks for triangles that are completely encompassed by other triangles. These triangles represent trains that are clearly inferior to the encompassing trains; that is, they are dominated by other trains. In Figure 4.4, train 121 is dominated by trains 142 and 148 because its triangle boundaries are completely encompassed by trains 142 and 148. As a result, this train may be discarded from further evaluation because its attributes of cost, time, and performance are less desirable than the same attributes for other trains - in this case, train 142 and 148.

From the results presented thus far, it is clear that screening the trains from 58 to a lesser set that exhibit desired attributes is not as straight-forward as one would hope. Based upon dominance considerations of the raw factors, trains 3, 4, 142, and 148 are the clear choice. Based on utility considerations which recognize weightings of the factors, trains 135, 136, 141, 142, 147, and 148 are the top contenders. Table 4.3 shows the top candidates based on both dominance and overall utility scores.

Table 4.3 Summary of Top Ranked Trains

Train	Utility Score	Notes
3	0.717	Ranked no. 25 in utility and not dominated by other trains
4	0.526	Ranked no. 32 in utility and not dominated by other trains
135	0.917	Ranked no. 3 in utility
136	0.913	Ranked no. 6 in utility
141	0.915	Ranked no. 5 in utility
142	0.936	Ranked no. 1 in utility and not dominated by other trains
147	0.915	Ranked no. 4 in utility
148	0.927	Ranked no. 2 in utility and not dominated by other trains

From Table 4.3, it is seen that there are 2 of the 4 trains (# 142 and # 148) that are not dominated by other trains, and score favorably using overall utility as a criteria. The other two trains that are not dominated (# 3 and 4) exhibit relatively low utility scores. Their low utility scores are due to their relatively low performance value which has a weight of 0.44 in the overall utility function. Train 3 performance level is 94%. Train 4 performance level is 90%.

At this point, it is important to reflect on the technologies that are represented by the train numbers. Trains 3 and 4 use Dynamic Underground Stripping as their primary remediation technology. These trains are USA trains. The other trains posted in Table 4.3 (135, 136, 141, 142, 147, and 148) use LASAGNA as the primary technology. These trains are U/S & A trains. From this analysis, it is clear that, based on the data provided and the assumptions used to model the decision situation, the trains shown in Table 4.3 are the best candidates for further evaluation.

This initial set of screened candidates was reviewed by the key decision makers during a meeting at the Paducah DOE facility. It was decided to conduct further analysis on trains 3, 4, 94, 119, 135, 148, and 156 (baseline). Table 4.3a shows the characteristics of each of these trains.

Table 4.3a Summary of Trains Selected by Decision Makers

Train	Utility Score	Notes
3	0.717	Ranked no. 25 in utility and not dominated by other trains
4	0.526	Ranked no. 32 in utility and not dominated by other trains
94	0.899	Ranked no. 7 in utility
119	0.763	Ranked no. 20 in utility
135	0.917	Ranked no. 3 in utility
148	0.927	Ranked no. 2 in utility and not dominated by other trains
156	0.522	Ranked no. 33 in utility

Trains 3 and 4 were chosen because they use a single technology pair to remediate the entire site, reducing the complications involved in applying several technology pairs to a site. Trains 94 and 119 were chosen because they represent the two phase vacuum extraction family of technologies. The DMs were interested in comparing these trains with LASAGNA trains. Trains 135 and 148 were chosen to represent the LASAGNA family of technologies. Train 156 was chosen to represent a baseline train. It uses soil vapor extraction for the unsaturated zone and pump and treat for the saturated zone and the aquifer.

4.3 Results and Analysis of Probabilistic Model (Phase 2)

Based on the screening model outputs, it was decided to run the probabilistic model at performance levels of 80%, 85%, 90%, 95%, and 99%. The data used to drive the calculations performed in the model is found in Appendix I. The results of these runs are summarized numerically in Tables 4.4, 4.5, and 4.6.

Table 4.4 Time Required for a Given Performance Level

| Performance Desired | Time Required (Years) | | | | | | |
| | Train Numbers | | | | | | |
	3	4	94	119	135	148	156
80%	1.1	1.3	13.6	1.2	2.4	42.3	41.2
85%	2.3	4.8	17.1	1.9	2.9	51.2	50.4
90%	3.4	17.3	21.4	2.8	3.5	60.2	59.9
95%	4.5	N/A	N/A	3.6	4.2	69.4	70.0
99%	5.4	N/A	N/A	4.3	N/A	77.1	78.5

Table 4.5 Total Cost for a Given Performance Level

Performance Desired	Expected Total Cost (Millions of Dollars) Train Numbers						
	3	4	94	119	135	148	156
80%	0.6	2.4	9.4	2.4	2.0	4.7	9.1
85%	1.0	3.0	10.8	3.2	2.3	5.0	10.0
90%	1.3	4.9	12.4	3.9	2.8	5.2	10.7
95%	1.6	N/A	N/A	4.8	3.2	5.4	11.4
99%	1.9	N/A	N/A	5.5	N/A	5.5	11.8

Table 4.6 Overall Utility for a Given Performance Level

Performance Desired	Expected Value of Overall Utility Train Numbers						
	3	4	94	119	135	148	156
80%	0.55	0.52	0.36	0.52	0.53	0.37	0.30
85%	0.54	0.51	0.32	0.51	0.53	0.37	0.29
90%	0.54	0.40	0.27	0.50	0.52	0.36	0.28
95%	0.75	N/A	N/A	0.71	0.73	0.58	0.49
99%	0.92	N/A	N/A	0.87	N/A	0.76	0.66

Tables 4.4, 4.5, and 4.6 display all of the important values that were extracted from numerous runs of the probabilistic model. Note that the N/A entries denote that the data used to generate the tables does not exist for the specific conditions. For example, in Table 4.4, in the train 4 column and 95% performance row, N/A denotes that train 4 is not expected to reach a performance level of 95%. To gain better insight into the data presented in Tables 4.4, 4.5, and 4.6 a number of plots were developed. The plots contained in Figures 4.5 and 4.6 display the data contained in Table 4.4. The plots presented in Figures 4.7 and 4.8 display the data contained in Table 4.5. The plots shown in Figures 4.9 and 4.10 display the data contained in Table 4.6.

Figure 4.5 graphically shows the expected amount of time that each train will take

to reach a given performance level.
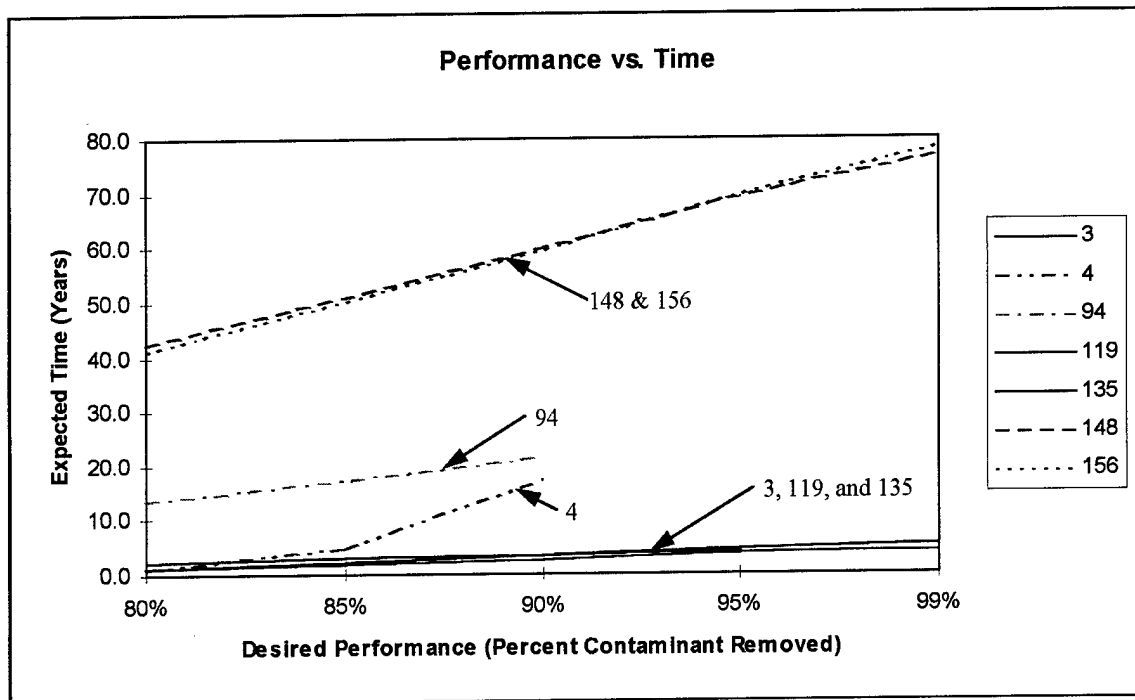
Figure 4.5 Desired Performance vs. Expected Time Required for Each Train

From Figure 4.5, it is seen that trains 148 and 156 (the baseline) are expected to take a

much greater amount of time to reach the same performance levels as the other trains. It

is also seen that trains 94 and 4 are expected to provide a maximum performance level of

90%. Train 4 also has a peculiar knee in its performance/time relationship. It is expected

to reach 80% performance in approximately 1.2 years, 85% in 5.5 years, but is not

expected to reach 90% until approximately 16.3 years. The three trains bunched together

at the bottom of the plot (3, 119, and 135) are the trains of most interest because they

yield the best performance in the least amount of time. Figure 4.6 was developed to further investigate these trains.
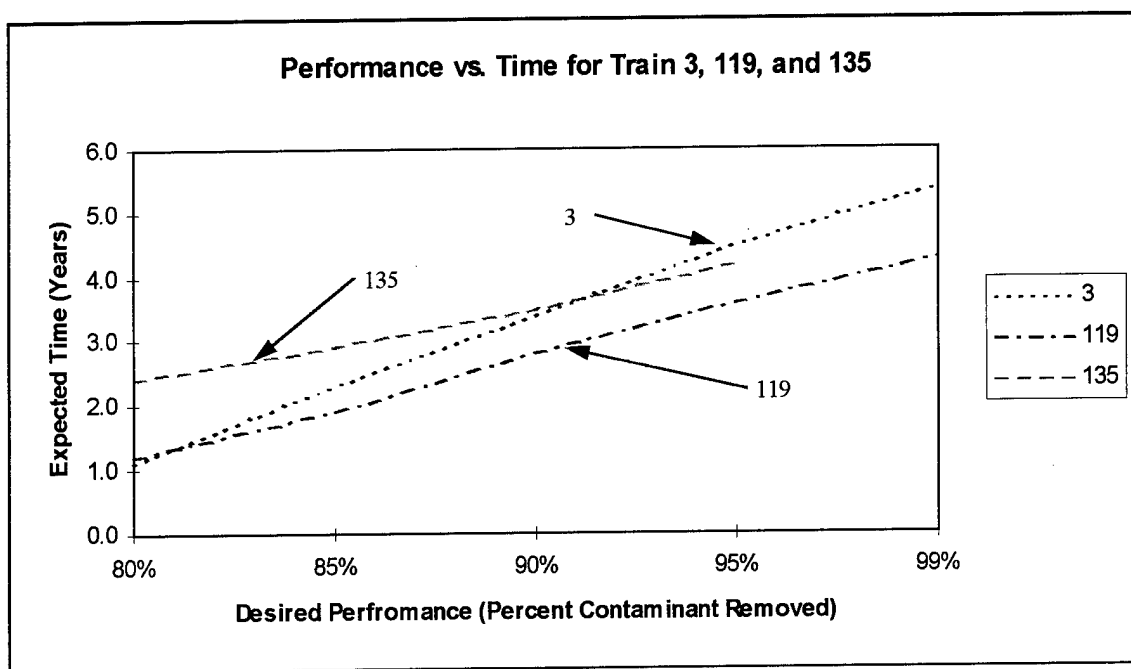
Figure 4.6 Desired Performance vs. Expected
Time Required for Trains 3, 119, and 135

From this plot (Figure 4.6), it is seen that train 119 achieves the highest

performance level in the least amount of time. This is followed by train 3, and finally by

train 135. Note, however, that train 135 is expected to reach a maximum of 95%

performance. The others (3 and 119) reach their maximum at a 99% performance level.

Of mild interest is the point where train 3 and 135 cross. If one were to choose between

these two trains based solely on performance, train 3 would be preferred unless it was

desired to rapidly reach performance in the range of 91% to 95%. In this range, train 135

would be the best choice between the two. Above 95%, train 3 would again be preferred

over 135 because 135 is not expected to reach a performance level beyond 95%.

At this point in the analysis, it is clear that of the 7 trains selected by the DMs for

further analysis, three have emerged as top candidates with respect to the expected

amount of time required for a given performance level. The next area investigated was the

cost of each train at a given performance level. Figure 4.7 shows the cost of each train at

a given performance level. The operating costs for each train were discounted at 2.5% per

year.
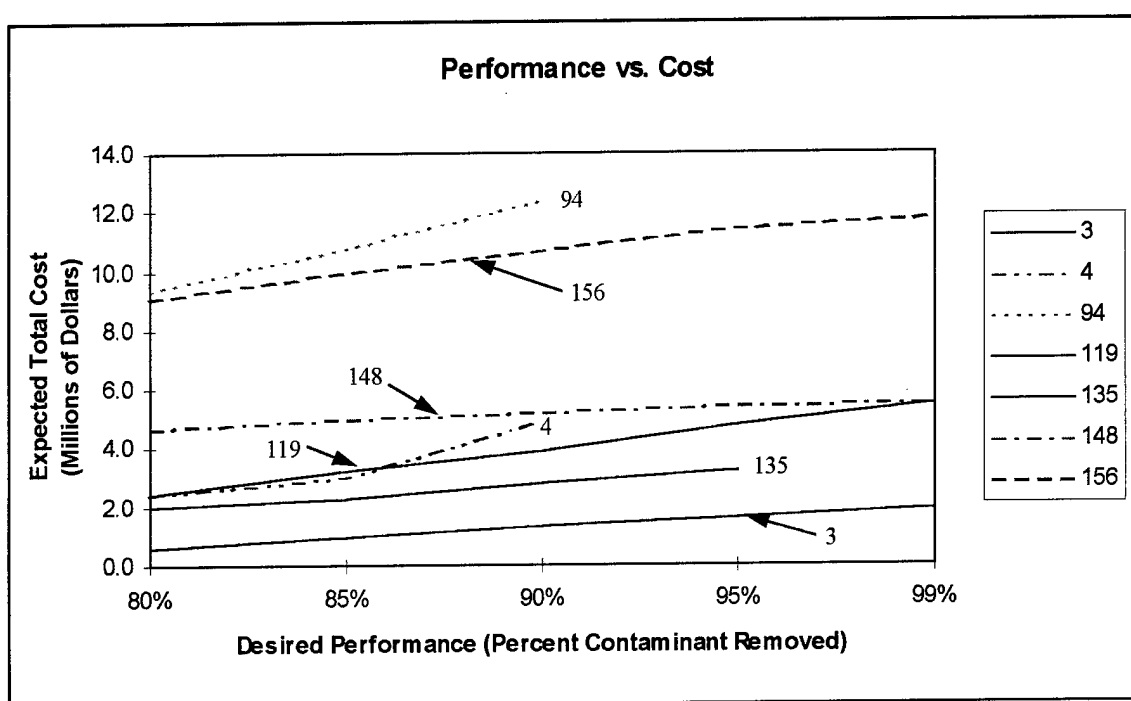
Figure 4.7 Desired Performance vs. Expected Total Cost

Figure 4.7 shows that train 94 is expected to be the most costly due to its operating costs

which are relatively high ($625,713/year) and its 21.4 year operating time. Train 156 (the

baseline) also indicates very high costs due to the long operating time required to reach a

desirable performance level. Train 156 takes approximately 60 years to reach a level of

90% performance. Train 148 also is expected to take approximately 60 years to reach

90% performance, but its operating costs are approximately 1/3 of train 156. Train 4

again shows a distinctive knee due to its performance characteristics and the large amount

of time required for this train to move from 85% to 90% performance. Trains 3, 119, and

135 emerge again as the best with respect to NPV costs and are plotted in more detail in

Figure 4.8.
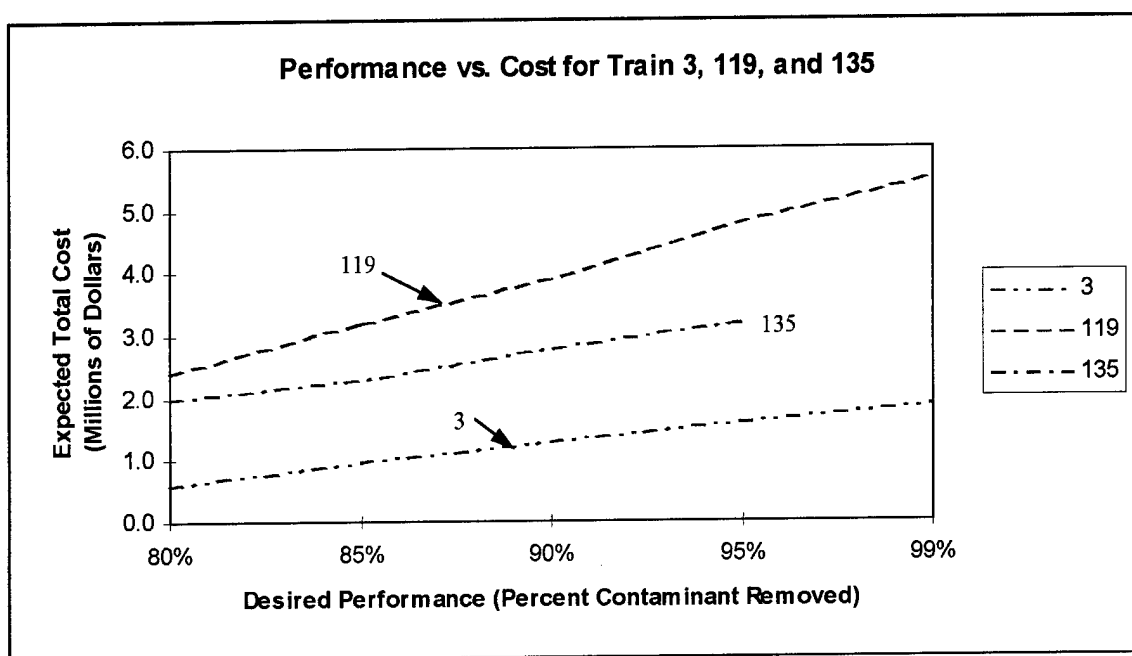
Figure 4.8 Desired Performance vs. Expected
Total Cost for Train 3, 119, and 135

From Figure 4.8 it is clear that train 3 is the top performer with respect to cost,

135 is second, and 119 is third. Note that train 135 is not expected to perform better than

95%, whereas the other two can potentially reach a 99% performance level.

The final area that was used to investigate the seven trains was overall utility.

Using the utility functions and weights (cost weight = 0.44, time weight = 0.12,

performance weight = 0.44) described in Section 3.4.1, the overall utility was calculated

for each train. The results are shown in Figure 4.9.
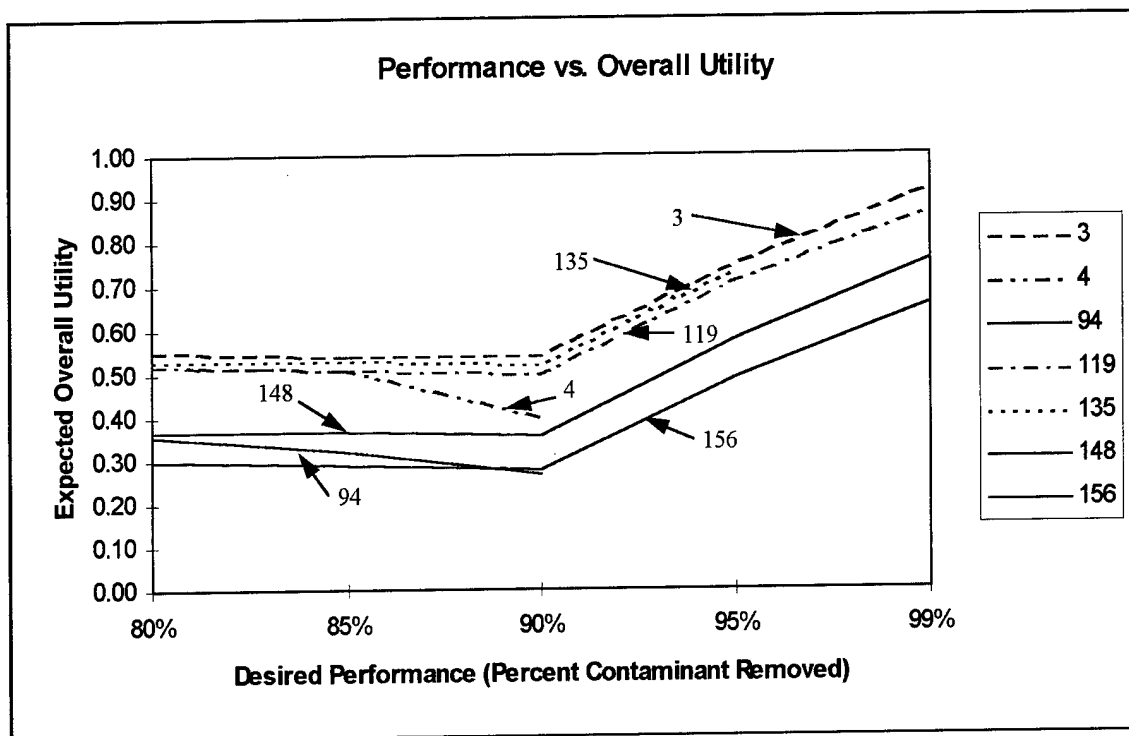
Figure 4.9 Desired Performance vs. Expected Overall Utility

From this figure, it is seen that the same trains (3, 119, and 135) are the top

candidates with respect to overall utility. Note that train 4 exhibits its characteristic knee

again. The reason for this is the same as previously stated. Note also that the trains do

not increase in overall utility until they reach 90% performance. The reason for this is that

the contribution to overall utility from performance does not "kick in" until a train reaches

the 90% performance level.

To further investigate the top candidates, trains 3, 119, and 135 are plotted in

more detail in Figure 4.10.
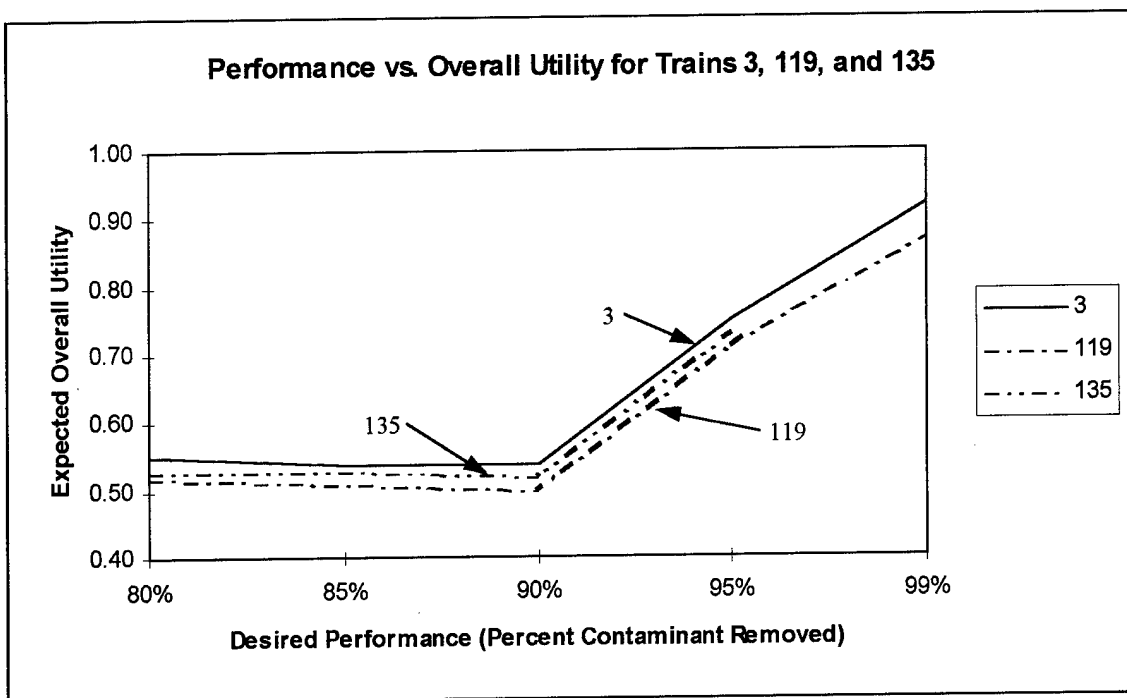
Figure 4.10 Desired Performance vs. Expected
Overall Utility for Train 3, 119, and 135

From this figure, it is clear that, with respect to overall utility, the top three

candidates exhibit similar characteristics. Again, overall utility increases rapidly as the

performance increases past 90%.

From the analysis thus far, it is quite clear that there are three trains that have

proven to be the top candidates in each of the measures. These trains and the technologies

employed by each are summarized in Table 4.7.

Table 4.7 Top Three Trains

Train	Strategy Type	Unsaturated Zone	Saturated Zone	Aquifer
3	USA	DUS & Bio	DUS & Bio	DUS & Bio
119	U/S & A	Two phase & None	Two phase & None	Oxidation & Bio
135	U/S & A	LASAGNA & None	LASAGNA & None	Oxidation & Bio

4.3.1 Sensitivity Analysis of Probabilistic Model

A key aspect of any analysis that can contribute to the confidence in the overall results is sensitivity analysis. At this point, the trains have been narrowed down to three top contenders. The critical questions of interest now are: Under what conditions will the top three trains remain the top contenders? If one or more of the parameters is varied, how will the solution change? To answer these questions, sensitivity analysis was conducted on capital costs, O&M costs, utility function weights, and interest rate for the top three trains (3, 119, and 135).

All of the sensitivity analysis was conducted at the 93% performance level. This level was selected as a representative performance value so that train 135 would not be excluded from the analysis. If a value greater than 95% were chosen, train 135 would not be included in the analysis because it can only reach a maximum performance level of 95%. If a value less than 90% were chosen, the utility contribution from performance would not be included in the analysis because of the performance utility function. The analysis could be conducted at any performance level specified by the decision maker(s).

Additionally, all of the sensitivity analysis was conducted using overall utility as the measure of merit. For discussion purposes, and comparisons, this measure is the most straight forward. It is assumed that train 3 is the top candidate, 135 is the next most promising candidate, and 119 is the third ranked train. Train 3 has the highest overall utility score, 135 next highest, and 119 the third highest. This is confirmed (Figure 4.10) by the fact that the three lines do not cross each other.

The capital costs for each of the remaining trains (3, 119, and 135) were separately varied by ± 50%. At the 93% performance level, the overall utility ranking did not change. Train 3 held steady as the best choice. This was followed by train 135 and then train 119. In other words, the ranking of the trains by overall utility at the 93% performance level is not sensitive to changes in the capital costs of the three trains. This is important because the capital cost figures may have a large margin of error. It is suspected that regardless of the performance level used to conduct this sensitivity analysis, the result would be the same. The main reason for this is due to the shape of the cost utility function which ranges from zero to $30 million. Because the costs used in this analysis were roughly one order of magnitude less, a change of ± 50% in capital costs is unlikely to affect the overall utility scores significantly. A reduction of this range may be warranted.

In a similar manner, the O&M costs were varied by ± 50% for the three trains (3, 119, and 135). A policy change was not realized as a result of the ranging, however, there were two rank changes that resulted from ranging the O&M costs of trains 119 and 135 at the 93% performance level. When the O&M costs for train 119 was varied below approximately $750,000, train 119 ranked ahead of train 135. Likewise, when train 135 O&M costs were varied to greater than approximately $1.1 million, train 119 ranked ahead of 135 in overall utility. Regardless of the ranging, however, train 3 always ranked number 1 in overall utility. The reason for the stability in overall utility is, again, due to the shape and wide range of the cost utility function.

To determine the sensitivity of the decision policy to the weights used in the overall utility function, each of the weights were individually ranged from zero to one.

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Note that during the ranging process the weights were forced to always sum to 1.0. The results indicated that at the 93% performance level, the performance weight could range from zero to one without instigating a policy change. The other two weights (cost, and time) yielded a policy change when they were varied. These results are shown graphically in Figures 4.11 and 4.12.

Sensitivity to Cost Weight
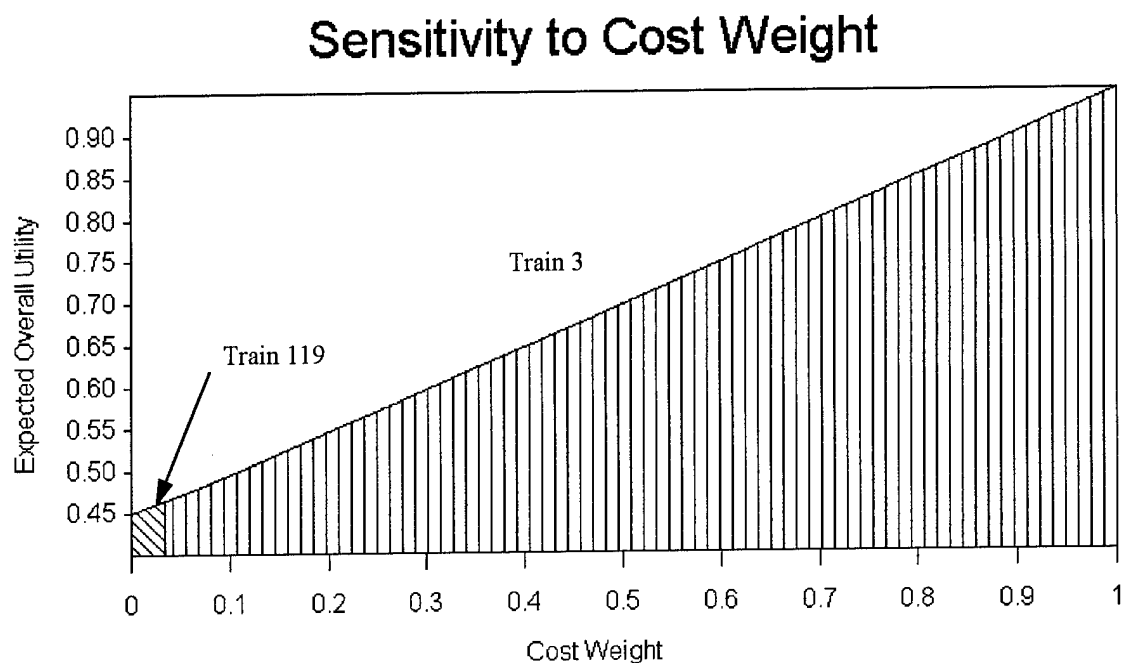
Figure 4.11 Sensitivity to Cost Weight

From Figure 4.11, it is seen that, at a 93% performance level, the optimal policy, or best train, changes when the cost weight is set to below approximately 0.05. At that point, the "best" train, in terms of overall utility, is 119. Otherwise, train 3 remains the best selection in terms of overall utility.

Sensitivity to Time Weight
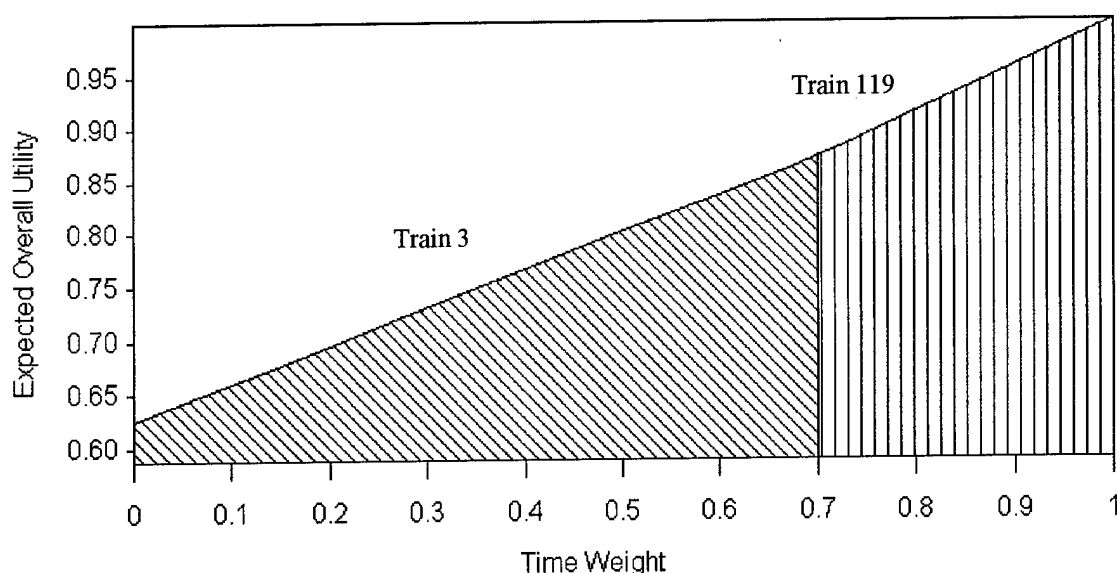
Figure 4.12 Sensitivity to Time Weight

Figure 4.12 shows that the best train in terms of overall utility changes when the time weight is ranged above approximately 0.68. At that point, train 119 becomes the train of choice in terms of overall utility at the 93% performance level.

The final sensitivity analysis was conducted on the interest rate used for the NPV calculations. The interest rate was ranged from 1% to 10% without causing a change in either the optimal decision policy (train 3) or a reordering of the top three trains. In other words, the overall utility score is insensitive to interest rate below 10%. The nominal interest rate used for all of the calculations was 2.5%, but any percentage between 1 and 10 could have been used and the relative results would be the same.

In summary, at the 93% performance level, using overall utility as a measure of merit, it is evident that the top three trains will remain the top three under a wide range of parameter variations. It was seen that the capital costs for all three of the trains could be

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varied by ± 50% without realizing a change in the optimal decision policy (train 3).

Additionally, varying the O&M costs by ± 50% did not yield a decision policy change, however some minor reordering of the top three trains occurred. It was also shown that by varying the cost weight assignment of the utility function, the optimal decision policy changes when it is set below approximately 0.05. Likewise, varying the time weight assignment of the utility function instigates a policy change when it is set above approximately 0.68. Lastly, it was seen that the interest rate could be ranged quite significantly without a policy change or a reordering of the top three trains. In short, it is quite evident that, at the 93% performance level, the top three trains (3, 119, and 135) have been captured, and they are quite robust to value changes. It appears these three trains remain quite robust over a fairly large performance range as well, given the initial data and assumptions.

4.3.2 Probabilistic Model Risk Discussion

To gain insight into the risks associated with the selection of a given train, it is helpful to plot cumulative risk profiles. Cumulative risk profiles show the chances associated with potential outcomes. They are used to identify the relative riskiness of different alternatives, or in this case, trains [Clemen, 1996: 119]. One such risk profile is shown in Figure 4.13. It is a cumulative risk profile based on a 93% performance level.
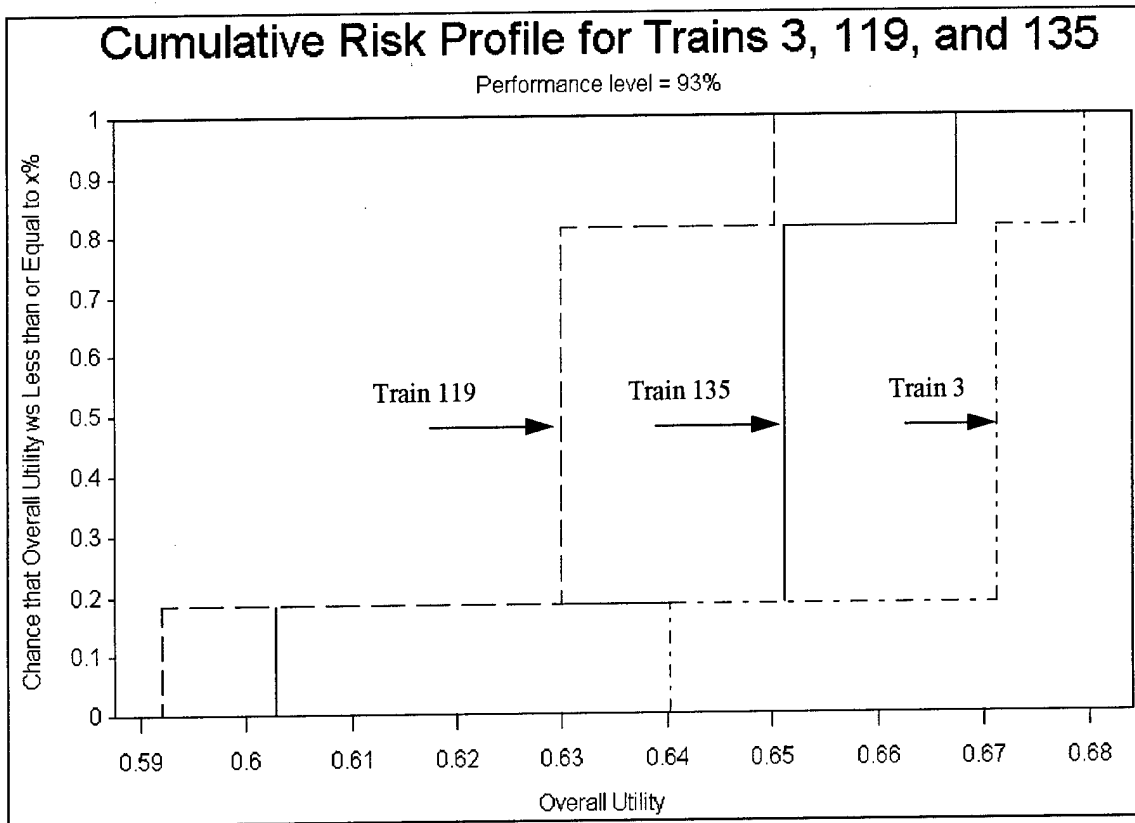
Figure 4.13 Cumulative Risk Profile for Overall Utility of Trains
Number 3, 119, and 135: Performance Level = 93%

From Figure 4.13 it is seen that train 3 stochastically dominates the other two

trains with respect to overall utility. In addition, train 135 stochastically dominates 119.

This indicates that at a performance level of 93%, if confidence was high that the data was

accurate, a decision maker would not select train 135 or 119 over train 3. Therefore,

based on the cumulative risk profile, for a 93% performance level, and for overall utility as

the measure of merit, it can be concluded that trains 119 and 135 can be dropped from

further evaluation. The remaining train (number 3) stochastically dominates the others.

Another insight can be gained from the cumulative risk profile. Focusing on train

3, in Figure 4.13, it is seen that there is approximately an 18% chance that the overall

utility will be 0.64 or less. In addition, there is a 81.5% chance that the overall utility will

be approximately 0.67 or less. There is a 100% chance that the overall utility will be approximately 0.68 or less. This information provides the DM with insight regarding the probabilities associated with a given outcome. Of course, these ranges are not extremely wide.

The same analysis can be conducted for the expected amount of time required to achieve a given performance level. One such cumulative risk profile is shown in Figure 4.14. This figure shows the potential ranges of the amount of time required to achieve a performance level of 93% and the probabilities associated with each value.

Cumulative Risk Profile for Train 3, 119, and 135
Performance level = 93%
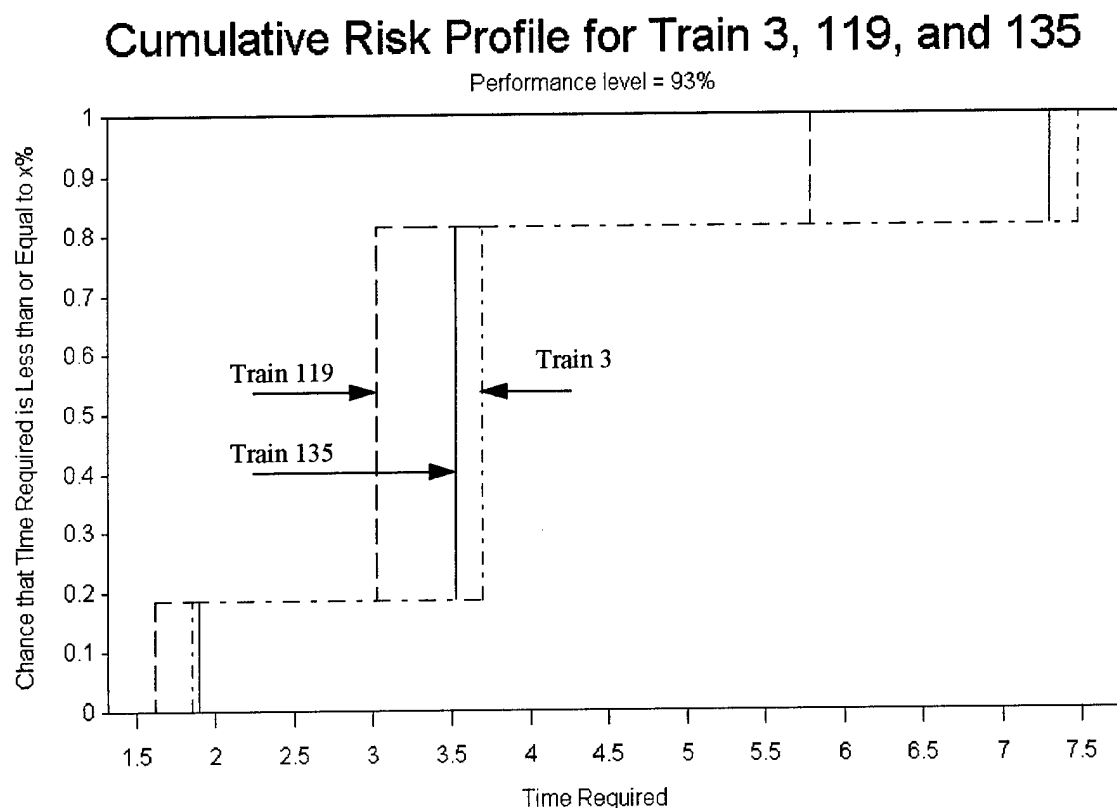
Figure 4.14 Cumulative Risk Profile for Time Required of Trains
Number 3, 119, and 135: Performance Level = 93%

From this figure, it is seen that at a performance level of 93%, with respect to the time required to achieve that performance level, train 119 stochastically dominates trains 3 and 135. These trains (3 and 135) risk a higher number of operating years to reach the same performance level. Therefore, theoretically, trains 3 and 135 could be discarded from further consideration *if* time required were the only criteria used as a measure of merit and one had complete confidence in the data used to generate Figure 4.13.

Figure 4.14 also shows the probabilities associated with specific time requirements necessary to achieve the 93% performance level. This information is summarized in Table 4.8.

Table 4.8 Summary of Time Required and Associated Probabilities

at 93% Performance Level

Probability Category	Train 3	Train 119	Train 135
18.5% chance that time required will be less than or equal to:	1.8	1.6	1.8
81.5% chance that time required will be less than or equal to:	3.7	3.0	3.5
100% chance that time required will be less than or equal to:	7.5	5.7	7.2

Figures 4.13 and 4.14 are one of many potential cumulative risk profiles that can be generated. They were selected to continue the discussion relating to 93% performance level that was started at the beginning of the Section 4.3.1. The expected time results and their associated probabilities were also determined for levels other than 93%. The results of these runs are shown in Table 4.9. This table shows the increases in times and costs due to desired performance level increases.

Table 4.9 Summary of Time Required and Associated Probabilities
at Various Performance Levels

Train	Times are in years *Costs are in millions of dollars*	Performance Level				
		80%	85%	90%	95%	99%
3	Expected Value of time/*cost* required	1.1/*0.6*	2.3/*1.0*	3.4/*1.3*	4.5/*1.6*	5.4/*1.9*
	18.5% chance that time required/*cost expected* will be less than or equal to:	0.5/*0.4*	1.1/*0.6*	1.5/*0.7*	2.1/*0.9*	2.5/*1.0*
	81.5% chance that time required/*cost expected* will be less than or equal to:	0.9/*0.5*	2.0/*0.9*	3.1/*1.2*	4.1/*1.5*	5.0/*1.8*
	100% chance that time required/*cost expected* will be less than or equal to:	2.5/*1.0*	4.3/*1.6*	6.0/*2.2*	8.3/*2.7*	10.0/*3.2*
119	Expected Value of time/*cost* required	1.2/*2.4*	1.9/*3.2*	2.8/*3.9*	3.6/*4.8*	4.3/*5.5*
	18.5% chance that time required/*cost expected* will be less than or equal to:	0.5/*1.8*	1.0/*2.2*	1.5/*2.6*	1.8/*3.0*	2.0/*3.3*
	81.5% chance that time required/*cost expected* will be less than or equal to:	1.0/*2.2*	1.8/*3.0*	2.5/*3.8*	3.3/*4.5*	4.0/*5.1*
	100% chance that time required/*cost expected* will be less than or equal to:	2.5/*3.8*	3.5/*4.7*	5.0/*5.9*	6.5/*7.4*	8.1/*8.9*
135	Expected Value of time/*cost* required	2.4/*2.0*	2.9/*2.3*	3.5/*2.8*	4.2/*3.2*	N/A
	18.5% chance that time required/*cost expected* will be less than or equal to:	1.2/*1.2*	1.5/*1.4*	1.7/*1.6*	2.0/*1.7*	N/A
	81.5% chance that time required/*cost expected* will be less than or equal to:	2.2/*1.9*	2.7/*2.2*	3.2/*2.6*	3.8/*2.9*	N/A
	100% chance that time required/*cost expected* will be less than or equal to:	3.9/*3.0*	5.0/*3.8*	6.4/*4.6*	8.0/*5.6*	N/A

Note: Data convention: time value/*cost value*

Note that, in theory, a cumulative risk profile could be generated for every conceivable

performance level.

V. Summary, Conclusions, and Recommendations

5.1 Summary of Analysis and Results

Based on the results and analysis provided in the previous sections, a clearer

picture of the decision situation has emerged for the data and assumptions of the analysis.

From an initial deterministic analysis, using utility and dominance theories as well as

significant input from the DM's, the number of candidate trains was reduced from

approximately 13 million to 7. Of these 7 trains, three (3, 119, and 135) emerged as the

best in terms of expected overall utility, cost, and time required. It was seen that the

remaining 4 trains would take significantly more time to reach desired performance levels,

and therefore, because of the resultant costs, were driven out of contention.

A sensitivity analysis was conducted on capital and O&M costs, attribute weights,

and the interest rate. This analysis indicated that the top three trains are quite robust and

not very sensitive to changes in any of these parameters at the 93% performance level.

By examining stochastic and deterministic dominance, it was seen that at the 93%

performance level, train 3 stochastically dominated the others with respect to overall

utility. It was also seen that at the 93% performance level, train 119 stochastically

dominated the others with respect to the time required to achieve that performance level.

5.2 Conclusions

Using the data given, the utility functions and weights derived from the DM's, the

trains that emerged as the top contenders are presented in rank order in Table 5.1. The

justification for this screening is based on one or more of the following considerations presented in Chapter 4:

- Dominance - Out of 58 trains, 4 were not dominated.

- Deterministic Utility scores - Based on the deterministic analysis (phase 1), 6 trains were selected for further evaluation. The remainder exhibited inferior utility scores. These were combined with the nondominated set to make up the initial screened trains.

- Decision Maker Selections - Based on a presentation of the deterministic analysis, the key decision makers selected 7 trains for further evaluation. At this point 88% of the trains were screened from further analysis.

- Probabilistic Utility Scores - Based on the probabilistic modeling of time, given a performance level, the remaining 7 trains were further analyzed. From this analysis, 3 trains (3, 119, 135) emerged as top contenders.

- Probabilistic Performance Analysis - To further analyze the 7 remaining trains, an in-depth analysis of the performance/time characteristics was accomplished. Additionally, performance ranges were investigated. This investigation revealed the potential time required variations for the top three trains.

- Sensitivity Analysis - To gain an understanding of the sensitivity of specific parameters and their effects on the outcome of train selection, a sensitivity analysis was conducted on the capital and O&M costs, attribute weights, and interest rate. It indicated that very little sensitivity existed in the analysis.

Table 5.1 Top Three Trains

Train Number and Description	Discussion
3 - This is a USA Train which uses Dynamic Underground Stripping and Biological Remediation Techniques	Train with consistently high utility scores across most of the time values. Also a train that is not dominated by any of the other 58 trains.
119 - This is a U/S & A Train which uses Two Phase Heating for the Unsaturated zone and the Saturated zone and then uses Oxidation combined with Biological Remediation for the Aquifer	Train with very good utility scores. Also, this train quickly achieves a high level of performance. This train, however, was dominated by trains no. 78 and 94 during the phase 1 screening analysis. It is also the most expensive of the three.
135 - This is a U/S & A Train which uses LASAGNA for the Unsaturated zone and the Saturated zone and then uses Oxidation and Biological Remediation for the Aquifer	Train maintains good utility scores, achieves a high level of performance quickly and is less expensive than train no. 119. This train, like no. 119, was shown to be dominated by trains no. 142 and 148

It should be noted that the most salient quality of the three trains shown in Table 5.1 was performance potential. These trains were able to perform at the 90% or better level very quickly, and thus received high utility scores and favorable performance ratings. The remainder of the trains (4, 94, 148, and 156) were found to be much less competitive than the three shown in Table 5.1.

If train 3 were selected, and it was desired to reach a 95% cleanup level, the costs are expected to range from $0.9 million to $2.7 million with an expected value of $ 1.6 million. The time required for this remediation scheme is expected to be approximately 4.5 years, but may be a little as 2.1 years or as much as 8.3 years. (See Table 4.9 for more in-depth results regarding other performance levels).

If train 119 were selected, and it was desired to reach a 95% cleanup level, the costs are expected to range from $3.0 million to $7.4 million with an expected value of $ 4.8 million. The time required for this remediation scheme is expected to be

approximately 3.6 years, but may be a little as 1.8 years or as much as 6.5 years. (See Table 4.9 for more in-depth results regarding other performance levels).

If train 135 were selected, and it was desired to reach a 95% cleanup level, the costs are expected to range from $1.7 million to $5.6 million with an expected value of $3.2 million. The time required for this remediation scheme is expected to be approximately 4.2 years, but may be a little as 2.0 years or as much as 8.0 years. (See Table 4.9 for more in-depth results regarding other performance levels).

Based on the results summarized here, it can also be concluded that the objectives of this research - specifically screening candidate trains - was accomplished. The research conducted provides the DOE with a quantitative justification and rationale for discarding 55 out of 58 (approximately 95%) candidate trains.

5.3 Recommendations for Further Research

The recommendations for further research are shown below:

- Data - More accurate data is needed. As mentioned in Chapter 3, the data used for this analysis was derived from a spill volume of 7,500 gallons. At present, it is believed that the spill volume may range from 2,000 to 500,000 gallons (see Appendix J). The results of the analysis would be much more meaningful to DOE DMs if the data more closely approximated reality. Additionally, the cost, time, and performance, data used in this analysis does not reflect the difficulties that will likely be encountered due to the existing facility and underground wires and pipes. Incorporating these factors into the data would make the analysis more valuable to the DOE.

- Uncertainty - This is a side-bar to the bullet above. If data is to be collected, uncertainties surrounding the data should also be collected and reported. It will make future analysis more meaningful to DOE DM's. For example, capital and O&M cost ranges would be very helpful for gaining insight into the annual costs expected for a given train.

- CERCLA Criteria - Rather than using three attributes as decision criteria, the CERCLA criteria that has been established for Hazardous Waste Sites (See Appendix B). could be used.

- Scaleable data - Because the uncertainty surrounding the spill volume for this site is so great, data showing performance levels and their relationship to time for a number of potential spill volumes would be very valuable.

- Technical risks - An analysis of the technical risks associated with each of the technologies would be quite helpful. For example, what are the risks associated with a given train failing to meet its expected performance goal.

From this research and analysis, it is quite clear that making use of DA and MAUT techniques can be a valuable approach for quantitatively evaluating competing remediation trains. The DA approach assisted the DOE in their understanding of the decision situation and reducing the number of potential trains from over 13 million to the reasonable number of 58. The MAUT approach provided the DOE with a quantitative means to further screen the remaining 58 to a list of three top contenders.

In addition to the specific details provided for the WAG6, C-400 site, this research provides the DOE with a framework and easy to follow approach to evaluate other,

similar DNAPL sites. The analysis provided in this effort could easily be adapted by another analyst and applied to other sites contaminated with DNAPLs or other similar contaminants.

Appendix A: Specialized DA/MAUT Models

According to Jennings, Mehta, and Mohan, a number of specialized MAUT/DA models have been built over the past 15 years. Table A.1, based on the Jennings et al. work, provides a basic description of these models and identifies their specialized use.

Table A.1 MAUT Models Used for Specialized DA [Jennings et al., 1994: 1133 - 1135]

Model	Agency	Description	References
HRS (Hazardous Ranking System)	EPA	The model is (was) used to place waste sites on the National Priorities List (NPL). It is a simple model based on a composite weighted score: $S = S_M + S_{FE} + S_{DC}$ where S_M is the score for potential migration, S_{FE} is the score for potential explosion or fire hazards, and S_{DC} is the score for the potential to encounter a direct contact with the hazard. The model was used to generate the original list of 418 NPL sites in 1982.	Wu and Hilger, 1984: 797 - 807 Wells and Caldwell, 1990: 71 - 76
MEPAS (Multimedia Environmental Pollutant Assessment System)	DOE	Used to assess wildlife endangerment problems at DOE sites	Hartz and Whelan, 1988: 295 - 299 Droppo and Hopes, 1990: 193 - 205
RAAS (Remedial Action Assessment System)	DOE	Used during the Feasibility Study phase to provide alternatives guidance	Hartz and Whelan, 1988: 295 - 299
HAZRISK	DOE	Used in developing cost estimates and scheduling for projects involving hazardous waste cleanup	Hudson and Shangraw, 1990: 241 - 244

Model	Agency	Description	References
POS (Program Optimization System)	DOE	Used to optimize spending on restoration projects and to allocate remediation budgetary resources. The model is based on the following utility function: $U = W_{hs}U_{hs}X_{hs} + W_{rr}U_{rr}X_{rr} + W_{pc}U_{pc}X_{pc} - W_{rc}C_{rc} - W_{fc}C_{fc}$ Where the X's are performance scores for health and safety (hs), regulatory responsiveness (rr), and public concern (pc). The U's represent functions that define the utility of each X score. The W's are the importance weights, and the C's are the remaining (rc) and future (fc) costs.	Merkhofer, Cotton, Longo, 1988: 39 - 43
DPM (Defense Priority Model)	DOD	Used to estimate the risk to human health and the environment. Makes use of weighted scores that consider the source materials and their pathways to humans and the environment.	Expert, 1990
HARM (Hazard Assessment Risk Model)	Air Force	Predecessor to DPM	Hushon, 1990: 206 - 216
FLEX (Flexible Liner Expert)		Used to evaluate chemical compatibility of liners	Rossman and Siller, 1987: 113 - 127
HERPM (Human Exposure Potential Ranking Model)	NY Dept of Health	Used as a ranking tool to establish relative priorities for investigation and remediation of sites	Smith, Patrick, and Hudson, 1987: 158 - 161
DRASTIC	EPA	Used to preliminary assess hazardous waste sites. Acronym is from: Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone media, and hydraulic Conductivity model	Allert, Bennet, Lehr, Petty, and Hackett, 1987

Model	Agency	Description	References
CORA (Cost of Remedial Action)	EPA	Used as a costing tool for remedial actions	Chenu and Crenca, 1990: 162 - 175
PAST (Potential ARAR's Selection Tool)		Used to assist in the development of ARAR's (Applicable or Relevant and Appropriate Requirements for remediation projects	Greathouse and Clements, 1991:

Appendix B: National Contingency Plan Evaluation Criteria

There are nine criteria used to evaluate remediation projects [DOE/OR/07-1243&D3].

These nine are listed and explained below:

Threshold Criteria: (each alternative *must* meet to be the selected alternative)

1. Overall Protection of human health and the environment

- Addresses if an alternative can adequately protect human health and the environment in both the short and long-term, from unacceptable risks posed by hazardous substances, pollutants, or contaminants present at the site by eliminating, reducing, or controlling exposures to contamination.

2. Compliance with Applicable or Relevant and Appropriate Requirements (ARAR's)

- Assesses if the alternatives attain ARARs under Federal environmental laws and State environmental laws.

Balancing Criteria: (used to compare and weigh the major trade-offs among the alternatives)

3. Long-term effectiveness and permanence

- Assesses the ability of an alternative to provide long-term protection after remediation goals have been met.

4. Implementability

- Evaluates the ease or difficulty of implementing the alternatives.

5. Reduction of toxicity, mobility, or volume through treatment

- Evaluates the degree to which alternatives employ recycling or treatment that reduces toxicity. mobility, or volume, including how treatment is used to address the principal threats posed by the site.

6. Short-term effectiveness and permanence

- Addresses the time it takes for an alternative to be implemented and the potential effect on human health (including the community and workers) and the environment during implementation.

7. Cost

- Includes capital costs, including both direct and indirect costs, annual operation and maintenance (O&M)

Modifying Criteria: (used to modify an alternative or select a different alternative based on input from the State or the public)

8. State Acceptance

- Considers the concerns of the State on the alternatives.

9. Community Acceptance:

- Allows for a public comment period when interested persons and organizations can comment on the proposed remedy.

Adapted from DOE/OR/07-1243&D3 and GJPO-TP-11

Appendix C: Acronym Listing

CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CL	Contaminant Level
DA	Decision Analysis
DM	Decision Maker
DNAPL	Dense Non-Aqueous Phase Liquid
DOE	Department of Energy
DPL	Decision Programming Language
DQO	Data Quality Objective
ERBAM	Environmental Restoration Benefit Assessment Matrix
EV	Expected Value
MAUT	Multiattribute Utility Theory
NCP	National Contingency Plan
NPL	National Priorities List
NPV	Net Present Value
O&M	Operations and Maintenance
PCB	Polychlorinated Biphenyl
RF	Radio Frequency
RI/FS	Remedial Investigation/Feasibility Study
SO	Site Owner
SVE	Soil Vapor Extraction
TCE	Trichloroethylene
TIDM	Technology Investment Decision Model
TOC	Total Organic Content
VOC	Volatile Organic Compound
WAG6	Waste Area Group 6

Appendix D: Technology Candidates

This appendix contains a description of the candidate remediation technologies that have been selected for consideration at the C-400 site.

6 Phase Heating

This technology uses a six-pointed star configuration of electrodes placed in the ground to enhance the mobility of contaminants. When power is applied to the electrodes, the resistive heat volatizes the contaminants and produces steam that in-turn strips the pollutant in-situ. The volatized contaminants are then removed via SVE.

The unique six pointed star configuration allows for the uniform heating of the soil. The patented process breaks the conventional 3 phase electricity into a six phase system. This provides for less expensive soil heating that is estimated to be approximately 100 kWh per cubic meter of soil [DOE/EM-0248, 1995: 206].

Biological Treatment

Biological treatment or bioremediation makes use of existing microorganisms, primarily bacteria, to effectively destroy contaminants. The key to this technology is the injection of nutrients and air into the soil to stimulate the microorganisms growth. When the microorganisms are given the proper stimuli (nutrients), they can transform the contaminants to harmless products such as carbon dioxide and water. Because the microorganisms can be quite sensitive to changes in hydrogeology, a good description of the subsurface is necessary prior to injecting nutrients. Additionally, high concentrations

of contaminants may not be affected by microbial growth, and may even kill fledgling microbes. It is for this reason that field tests have shown that bioremediation works best around the periphery of a highly concentrated contaminant zone [National Research Council, 1995: 131 - 133].

Cosolvent Enhanced In-situ Treatment

Cosolvents, like surfactants, are used to enhance conventional pump and treat systems. Cosolvents are substances that, when mixed with water, can enhance the solubility of the contaminant. Typical cosolvents are: methanol, and acetone. The idea behind this technology is similar to that of surfactant flooding. The cosolvent agent is injected into the ground and the area is flooded. Then the pump and treat systems pump the liberated contaminant and the cosolvent from the ground for treatment. The cosolvent acts to increase the solubility of the contaminant as well as decrease the retardation factors present in the contaminant, especially in DNAPLs. An additional benefit of cosolvents is that occasionally (depending on the concentration levels of the cosolvent and the contaminant as well as the hydrogeology) bioremediation is stimulated and microbial growth occurs. This will increase the in-situ destruction of the contaminant [National Research Council, 1995: 148 - 149].

Dynamic Underground Stripping

This technology is actually a combination of three separate technologies:

1. Steam injection - Steam is injected around the periphery of a contaminated site to heat the subsurface and potentially vaporize the contaminants. This is done in the hopes that the contaminants will be driven to a central location and extracted via a SVE scheme.

2. Electrical Heating - Electrical probes are used in the areas that contain the highest concentration of contaminants. The heating will liberate the contaminants from the soil and drive them into the same area that the steam injection technology drove the vaporized contaminants.

3. Underground Imaging - Electrical Resistance Tomography is used as an imaging technique to provide assurance that the heated areas are cleaning up the site as expected. This technology can be used above and below the water table, and is especially well suited for subsurfaces where clay and sand are interlaced together [Mather, 1995: WWWeb].

LASAGNA™ or Electro-Osmosis

Electro-osmosis is a process that uses electrodes placed into the soil to mobilize DNAPL contaminants. Once power is applied to the electrodes, the DNAPL contaminant will migrate in sufficient quantities to warrant some form of removal or in-situ destruction. Typically, the contaminant is removed via adsorption or destroyed biologically. The technology appears to be most beneficial when contaminants are located in the saturated zone and where the soil has a low permeability.

The term LASAGNA™ was derived through a consortium of private companies that were researching methods to speed VOC contaminant cleanup. The researchers determined that a *layered* application of Electro-osmotic probes would speed the migration of the contaminants and thus increase the speed at which cleanup could occur.

It is because of this layered application that the term LASAGNA™ was born.

Subsequently, Monsanto (one of the consortium members) patented and trademarked the

process [Falta et al. 1996: 24].

Oxidation

Chemical Oxidation is an in-situ remediation technology that uses a chemical

oxidant solution such as hydrogen Peroxide (H_2O_2) or Potassium Permanganate ($KMnO_4$)

as an oxidant to degrade organic contaminants (like DNAPLs). The oxidant solution (i.e.

H_2O_2 or $KMnO_4$) is either injected into the ground or is mixed with the soil through a soil

mixing apparatus. Either way, the oxidant comes into contact with the organic DNAPL

contaminant, and destroys it [West, 1996].

Pump and Teat

Conventional pump and treat systems operate by pumping ground water to the

surface, removing the contaminants (typically through some type of air stripper) and

returning the water to the ground or into a municipal sewage plant. This technology has

been labeled old fashioned and inefficient because of the large volumes of water that must

be pumped out of the ground. Also, due to the chemical composition of DNAPL

contaminants, the fact that one has pumped contaminated water out of the ground does

not guarantee the complete cleanup of the site. The residual contaminants that adhere to

subsurface particles are not as susceptible to pump and treat systems [National Research

Council, 1995: 29].

Permeable Treatment Zones

This technology makes use of a permeable "wall" that is inserted into the subsurface. The wall allows ground water to flow through it. As the groundwater flows through, the composition of the encourages a chemical treatment of the contaminant. The most common type of PTZ wall is iron filings. The iron filings create a chemical reaction with the contaminant (i.e. TCE) and encourage is breakdown. As the water flows through the permeable barrier. the contaminant is trapped in the chemical reactions of the wall [Clayton, 1997].

Radio Frequency (RF) Heating

Radio Frequency (RF) heating uses the heat energy induced by the application of RF energy into the soil to enhance conventional vapor extraction methods. The heat applied to the soil through RF causes a liberation of the contaminants, especially Volatile Organic Compounds (VOCs) like TCE. This technology is most applicable to remediation of the vadose zone [DOE/EM-0248, 1995: 215 - 217].

Surfactant Enhanced In-situ Treatment

Surfactants (surface active agents) are used to enhance conventional pump and treat systems. They are categorized as part of the family of soil flushing. The idea behind this technology is to inject a surfactant into the ground and flood the area with a surfactant agent. Once the flood is complete, conventional pump and treat systems are used to recover both the contaminant and the surfactant. The surfactant acts as a loosening agent

to separate the contaminant from the water saturated soil [Falta et al., 1996:26 - 29 and National Research Council, 1995: 148 - 149].

Soil Vapor Extraction (SVE)

This technology uses extraction wells to draw gases from the ground in a vacuum style configuration. The gases drawn are typically air bubbles that have picked up contaminants in their journey to the extraction well head. The air bubbles, along with their molecules of contaminant are sucked into the vacuum/blower system, and treated above ground in an off-gas treatment system. This method is applicable above the water table (unsaturated zone) in highly permeable soils. It is typically used in conjunction with an enhancing technology such as air sparging or thermal heating technologies. SVE has been used for over ten years, especially in the remediation of petroleum hydrocarbons [Falta et al., 1996: 40 - 41]

Two Phase

This technology makes use of a powerful vacuum system that extracts soil gases and liquids. It is typically used in low permeability subsurfaces. As the vacuum is applied through the screened well head, soil vapors are extracted and groundwater is entrained by the extracted vapors. Once the vapors and groundwater are above ground, they are separated and treated individually. This technology can be combined with bioremediation, air sparging, or bio-venting. It is generally considered to be more effective than using SVE singularly [EPA/542/B-94/013, 1994: 4.145 - 4.147].

UVB

This technology is similar to pump and treat except that it does not use a well head like pump and treat does. The technology is used to pump contaminated groundwater to the surface, treat it using some form of air stripping, and then injecting it back into the subsurface. Typically this technology is used to affect a small area no larger than 50' in diameter. This is compared against pump and treat which can affect an area up to approximately 300' [Clayton, 1997].

Appendix E: Phase 1 (Screening Model) Decision Tree

The complete screening model decision tree is shown in Figure E.1. Figures E.2 through E.6 are enlarged views of each subsection of the overall decision tree.
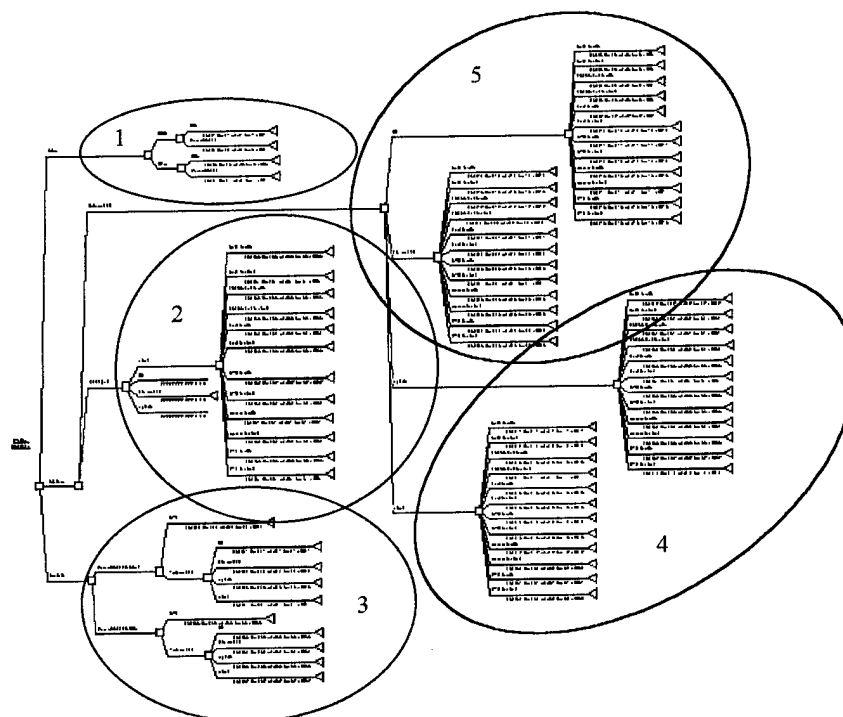
Figure E.1 Decision Tree
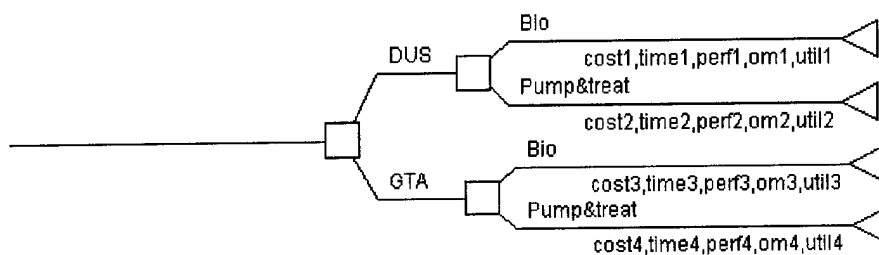
Figure E.2 Enlarged Section #1 of Decision Tree
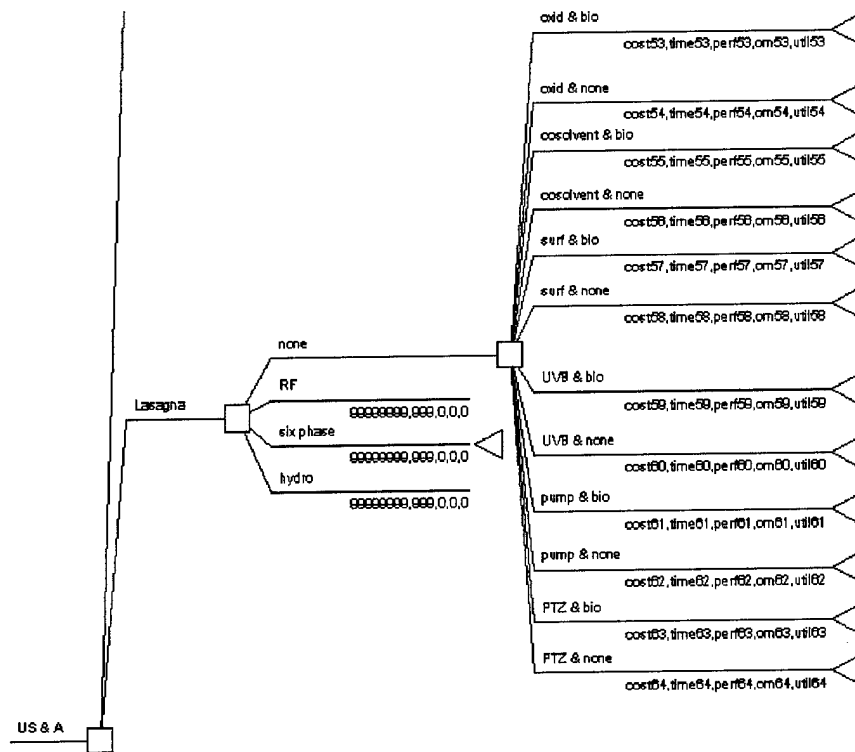
Figure E.3 Enlarged Section #2 of Decision Tree

E-2

SVE
cost70,time70,perf70,om70,util70

RF
cost71,time71,perf71,om71,util71

six phase
cost72,time72,perf72,om72,util72

Pump&treat & None

Two phase
hydro
cost73,time73,perf73,om73,util73

none
cost74,time74,perf74,om74,util74

,U

SVE
cost65,time65,perf65,om65,util65

RF
cost66,time66,perf66,om66,util66

Pump&treat & Bio

six phase
cost67,time67,perf67,om67,util67

Two phase
hydro
cost68,time68,perf68,om68,util68

none
cost69,time69,perf69,om69,util69

Figure E.4 Enlarged Section #3 of Decision Tree

oxid & bio
cost29,time29,perf29,om29,util29

oxid & none
cost30,time30,perf30,om30,util30

cosolvent & bio
cost31,time31,perf31,om31,util31

cosolvent & none
cost32,time32,perf32,om32,util32

surf & bio
cost33,time33,perf33,om33,util33

surf & none
cost34,time34,perf34,om34,util34

hydro

UVB & bio
cost35,time35,perf35,om35,util35

UVB & none
cost36,time36,perf36,om36,util36

pump & bio
cost37,time37,perf37,om37,util37

pump & none
cost38,time38,perf38,om38,util38

PT2 & bio
cost39,time39,perf39,om39,util39

PT2 & none
cost40,time40,perf40,om40,util40

oxid & bio
cost41,time41,perf41,om41,util41

oxid & none
cost42,time42,perf42,om42,util42

cosolvent & bio
cost43,time43,perf43,om43,util43

cosolvent & none
cost44,time44,perf44,om44,util44

surf & bio
cost45,time45,perf45,om45,util45

surf & none
cost46,time46,perf46,om46,util46

UVB & bio
cost47,time47,perf47,om47,util47

UVB & none
cost48,time48,perf48,om48,util48

pump & bio
cost49,time49,perf49,om49,util49

pump & none
cost50,time50,perf50,om50,util50

PT2 & bio
cost51,time51,perf51,om51,util51

PT2 & none
cost52,time52,perf52,om52,util52
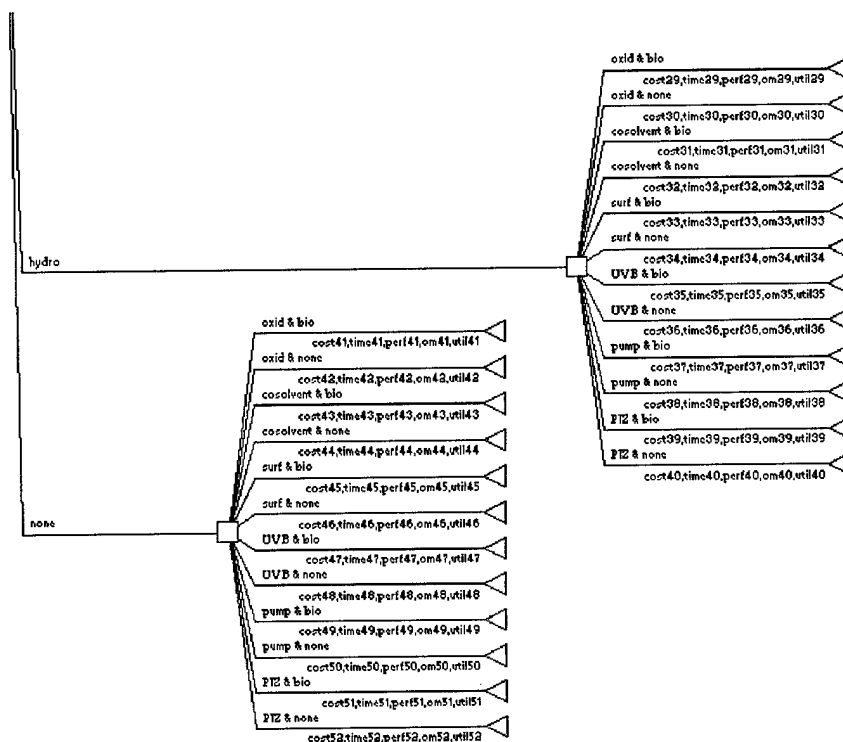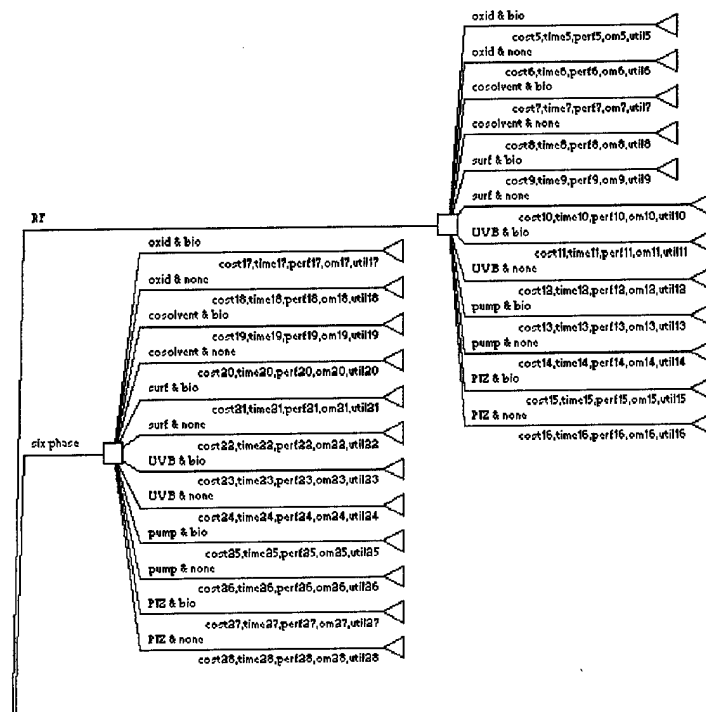
Figure E.5 Enlarged Section #4 of Decision Tree

Figure E.6 Enlarged Section #5 of Decision Tree

Appendix F: Data

Train descriptions are shown in Table F.1

Table F.1 Train Descriptions (page 1 of 2)

Train No.	Unsat		Sat		Aquifer	
3	Dynamic Underground Stripping	Biological	Dynamic Underground Stripping	Biological	Dynamic Underground Stripping	Biological
4	Dynamic Underground Stripping	Pump and Treat	Dynamic Underground Stripping	Pump and Treat	Dynamic Underground Stripping	Pump and Treat
71	Two-Phase Vacuum Extraction	Radio Frequency Heating	Two-Phase Vacuum Extraction	Radio Frequency Heating	Oxidation	Biological
72	Two-Phase Vacuum Extraction	Radio Frequency Heating	Two-Phase Vacuum Extraction	Radio Frequency Heating	Oxidation	None
73	Two-Phase Vacuum Extraction	Radio Frequency Heating	Two-Phase Vacuum Extraction	Radio Frequency Heating	Cosolvent Flushing	Biological
74	Two-Phase Vacuum Extraction	Radio Frequency Heating	Two-Phase Vacuum Extraction	Radio Frequency Heating	Cosolvent Flushing	None
75	Two-Phase Vacuum Extraction	Radio Frequency Heating	Two-Phase Vacuum Extraction	Radio Frequency Heating	Surfactant Flushing	Biological
76	Two-Phase Vacuum Extraction	Radio Frequency Heating	Two-Phase Vacuum Extraction	Radio Frequency Heating	Surfactant Flushing	None
77	Two-Phase Vacuum Extraction	Radio Frequency Heating	Two-Phase Vacuum Extraction	Radio Frequency Heating	UVB	Biological
78	Two-Phase Vacuum Extraction	Radio Frequency Heating	Two-Phase Vacuum Extraction	Radio Frequency Heating	UVB	None
79	Two-Phase Vacuum Extraction	Radio Frequency Heating	Two-Phase Vacuum Extraction	Radio Frequency Heating	Pump and Treat	Biological
80	Two-Phase Vacuum Extraction	Radio Frequency Heating	Two-Phase Vacuum Extraction	Radio Frequency Heating	Pump and Treat	None
83	Two-Phase Vacuum Extraction	Radio Frequency Heating	Two-Phase Vacuum Extraction	Radio Frequency Heating	Permeable Treatment Zone	Biological
84	Two-Phase Vacuum Extraction	Radio Frequency Heating	Two-Phase Vacuum Extraction	Radio Frequency Heating	Permeable Treatment Zone	None
87	Two-Phase Vacuum Extraction	Six-Phase Heating	Two-Phase Vacuum Extraction	Six-Phase Heating	Oxidation	Biological
88	Two-Phase Vacuum Extraction	Six-Phase Heating	Two-Phase Vacuum Extraction	Six-Phase Heating	Oxidation	None
89	Two-Phase Vacuum Extraction	Six-Phase Heating	Two-Phase Vacuum Extraction	Six-Phase Heating	Cosolvent Flushing	Biological
90	Two-Phase Vacuum Extraction	Six-Phase Heating	Two-Phase Vacuum Extraction	Six-Phase Heating	Cosolvent Flushing	None
91	Two-Phase Vacuum Extraction	Six-Phase Heating	Two-Phase Vacuum Extraction	Six-Phase Heating	Surfactant Flushing	Biological
92	Two-Phase Vacuum Extraction	Six-Phase Heating	Two-Phase Vacuum Extraction	Six-Phase Heating	Surfactant Flushing	None
93	Two-Phase Vacuum Extraction	Six-Phase Heating	Two-Phase Vacuum Extraction	Six-Phase Heating	UVB	Biological
94	Two-Phase Vacuum Extraction	Six-Phase Heating	Two-Phase Vacuum Extraction	Six-Phase Heating	UVB	None
95	Two-Phase Vacuum Extraction	Six-Phase Heating	Two-Phase Vacuum Extraction	Six-Phase Heating	Pump and Treat	Biological
96	Two-Phase Vacuum Extraction	Six-Phase Heating	Two-Phase Vacuum Extraction	Six-Phase Heating	Pump and Treat	None
99	Two-Phase Vacuum Extraction	Six-Phase Heating	Two-Phase Vacuum Extraction	Six-Phase Heating	Permeable Treatment Zone	Biological
100	Two-Phase Vacuum Extraction	Six-Phase Heating	Two-Phase Vacuum Extraction	Six-Phase Heating	Permeable Treatment Zone	None
119	Two-Phase Vacuum Extraction	None	Two-Phase Vacuum Extraction	None	Oxidation	Biological
120	Two-Phase Vacuum Extraction	None	Two-Phase Vacuum Extraction	None	Oxidation	None
121	Two-Phase Vacuum Extraction	None	Two-Phase Vacuum Extraction	None	Cosolvent Flushing	Biological
122	Two-Phase Vacuum Extraction	None	Two-Phase Vacuum Extraction	None	Cosolvent Flushing	None
123	Two-Phase Vacuum Extraction	None	Two-Phase Vacuum Extraction	None	Surfactant Flushing	Biological
124	Two-Phase Vacuum Extraction	None	Two-Phase Vacuum Extraction	None	Surfactant Flushing	None
125	Two-Phase Vacuum Extraction	None	Two-Phase Vacuum Extraction	None	UVB	Biological
126	Two-Phase Vacuum Extraction	None	Two-Phase Vacuum Extraction	None	UVB	None
127	Two-Phase Vacuum Extraction	None	Two-Phase Vacuum Extraction	None	Pump and Treat	Biological
128	Two-Phase Vacuum Extraction	None	Two-Phase Vacuum Extraction	None	Pump and Treat	None

Table F.1 Train Descriptions (page 2 of 2)

Train No.	Unsat		Sat		Aquifer	
131	Two-Phase Vacuum Extraction	None	Two-Phase Vacuum Extraction	None	Permeable Treatment Zone	Biological
132	Two-Phase Vacuum Extraction	None	Two-Phase Vacuum Extraction	None	Permeable Treatment Zone	None
135	LASAGNA	None	LASAGNA	None	Oxidation	Biological
136	LASAGNA	None	LASAGNA	None	Oxidation	None
137	LASAGNA	None	LASAGNA	None	Cosolvent Flushing	Biological
138	LASAGNA	None	LASAGNA	None	Cosolvent Flushing	None
139	LASAGNA	None	LASAGNA	None	Surfactant Flushing	Biological
140	LASAGNA	None	LASAGNA	None	Surfactant Flushing	None
141	LASAGNA	None	LASAGNA	None	UVB	Biological
142	LASAGNA	None	LASAGNA	None	UVB	None
143	LASAGNA	None	LASAGNA	None	Pump and Treat	Biological
144	LASAGNA	None	LASAGNA	None	Pump and Treat	None
147	LASAGNA	None	LASAGNA	None	Permeable Treatment Zone	Biological
148	LASAGNA	None	LASAGNA	None	Permeable Treatment Zone	None
151	Soil Vapor Extraction	None	Pump and Treat	Biological	Pump and Treat	Biological
152	Two-Phase Vacuum Extraction	Radio Frequency Heating	Pump and Treat	Biological	Pump and Treat	Biological
153	Two-Phase Vacuum Extraction	Six-Phase Heating	Pump and Treat	Biological	Pump and Treat	Biological
155	Two-Phase Vacuum Extraction	None	Pump and Treat	Biological	Pump and Treat	Biological
156	Soil Vapor Extraction	None	Pump and Treat	None	Pump and Treat	None
157	Two-Phase Vacuum Extraction	Radio Frequency Heating	Pump and Treat	None	Pump and Treat	None
158	Two-Phase Vacuum Extraction	Six-Phase Heating	Pump and Treat	None	Pump and Treat	None
160	Two-Phase Vacuum Extraction	None	Pump and Treat	None	Pump and Treat	None

Trains 3 and 4 are USA trains. Trains 71 through 148 are U/S & A trains. Trains 151 through 160 are S/A & U trains.

Table F.2 Attribute Values

Train No.	NPV Cost	O&M Cost	Time	Perf
3 *	1,421,159	336,558	3.50	94%
4 *	2,542,477	203,820	0.50	90%
71	5,781,615	737,648	5.93	99%
72	4,878,582	604,910	8.93	99%
73	8,862,873	426,315	7.67	90%
74	8,890,006	700,845	6.00	82%
75	7,771,542	426,315	7.67	94%
76	7,798,676	700,845	6.00	86%
77	5,942,740	430,126	5.67	99%
78	4,370,376	632,193	3.00	99%
79	5,568,950	426,315	5.67	90%
80	4,926,754	609,335	6.00	77%
83	5,903,458	426,315	6.17	99%
84	5,037,742	426,315	2.67	97%
87	5,759,190	737,648	5.93	99%
88	4,856,157	604,910	8.93	99%
89	8,840,448	419,835	7.67	90%
90	8,867,581	694,365	6.00	82%
91	7,749,117	419,835	7.67	94%
92	7,776,251	694,365	6.00	86%
93	5,920,314	430,126	5.67	99%
94 *	4,347,951	625,713	3.00	99%
95	5,546,525	419,835	5.67	90%
96	4,904,329	602,855	6.00	77%
99	5,881,033	419,835	6.17	99%
100	5,015,317	419,835	2.67	97%
119 *	4,635,890	1,056,083	3.26	96%
120	3,732,857	923,345	6.26	95%
121	8,647,315	725,703	5.00	85%
122	7,744,281	592,965	6.00	77%
123	7,555,984	725,703	5.00	89%
124	6,652,951	592,965	6.00	81%
125	4,797,014	748,561	3.00	96%
126	3,224,651	524,313	3.00	95%
127	5,353,392	725,703	3.00	85%
128	3,781,029	501,455	6.00	72%
131	4,757,733	409,945	3.50	95%
132	3,892,017	318,435	2.17	92%
135 *	2,949,999	737,648	4.56	99%
136	2,046,966	604,910	7.56	99%
137	6,031,256	315,758	6.30	95%
138	6,058,390	274,531	7.30	87%
139	4,939,926	315,758	6.30	99%
140	4,036,893	183,021	7.30	91%
141	3,111,123	430,126	4.30	99%
142	1,538,760	205,878	4.30	99%
143	2,737,334	315,758	4.30	95%
144	2,095,138	195,047	7.30	82%
147	3,071,842	103,537	4.80	99%
148 *	2,206,126	103,537	1.80	99%
151	3,171,860	407,268	3.00	64%
152	6,499,117	517,825	5.67	80%
153	6,476,692	511,345	5.67	80%
155	5,353,392	725,703	3.00	70%
156 *	2,888,180	316,627	6.00	40%
157	4,926,754	517,825	8.67	50%
158	4,904,329	511,345	8.67	50%
160	3,781,029	501,455	6.00	42%

All of the values shown in table F.2 were acquired through Mountain State Engineering (MSE) Corporation.

They were generated using a life cycle cost model owned and operated by MSE.

Iteration Number 1

At the onset of the project, the emphasis was to build a model that contained hydrogeological characteristics and their relationships to cost, time, and performance parameters for each strategy. The strategies are divided into two zones - the saturated, and the unsaturated zone. Figure G.1 shows an influence diagram of this early iteration.

From Figure G.1, it is seen that there are two decisions - which technology strategy to use for the unsaturated zone, and which one to use for the saturated zone. Based on these decisions, the cost, time, and technology effectiveness (performance) are determined and combined into a utility value. The utility scores for the unsaturated zone and the saturated zone are then combined into an overall utility score and reported as one number. Note that the hydrogeological considerations for both the unsaturated and saturated zone influence the technology effectiveness. This was an important modeling consideration in this early version.

This model, however, was discarded because of a lack of relevant data relating hydrogeologic characteristics to technology effectiveness parameters.
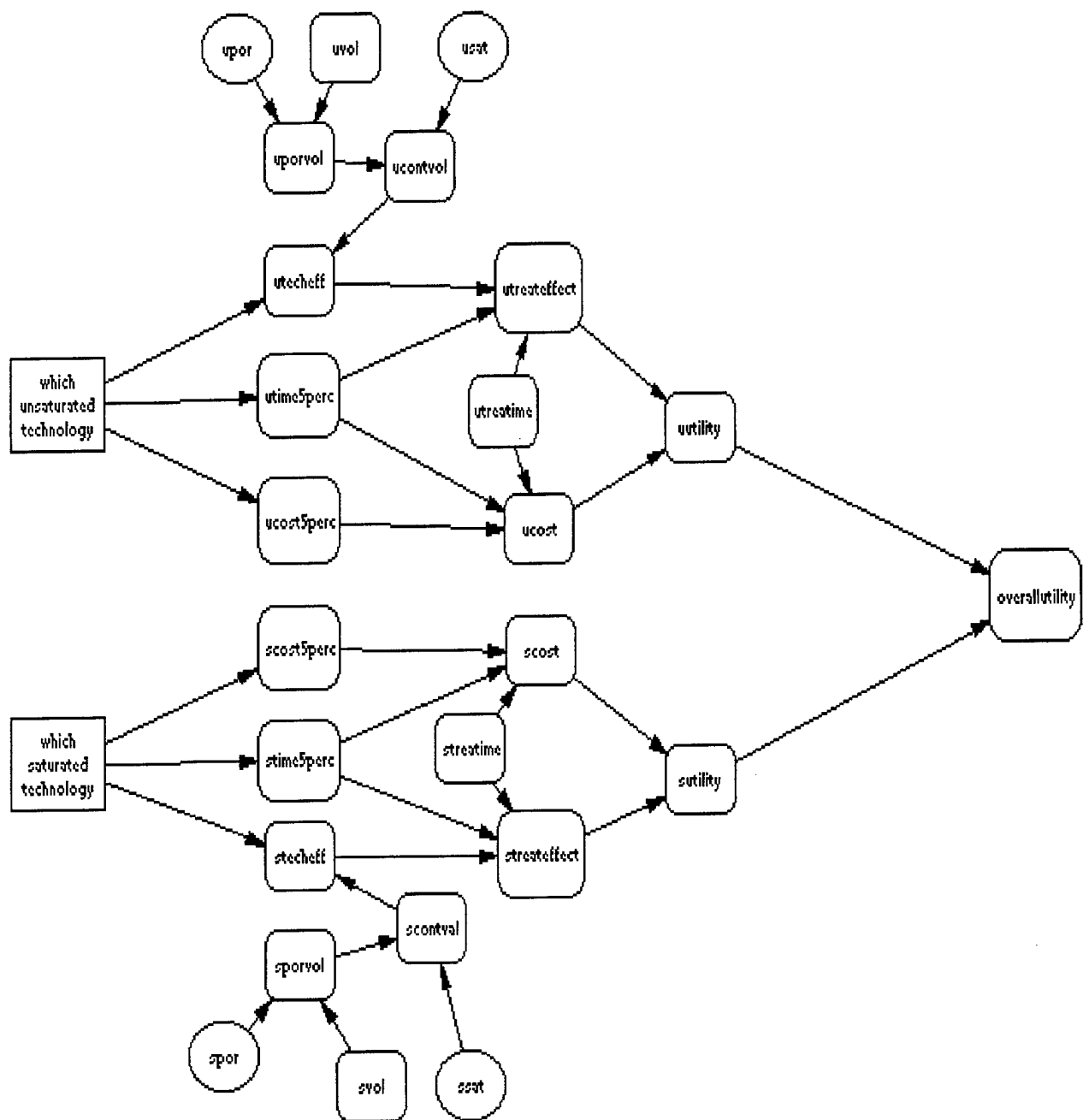
Figure G.1 Influence Diagram, Iteration 1

Iteration Number 2

The second iteration contained a number of changes - most notably the deletion of influencing relationships between hydrogeological characteristics and effectiveness levels and the addition of three more zones. Figure G.2 shows an influence diagram of this iteration.
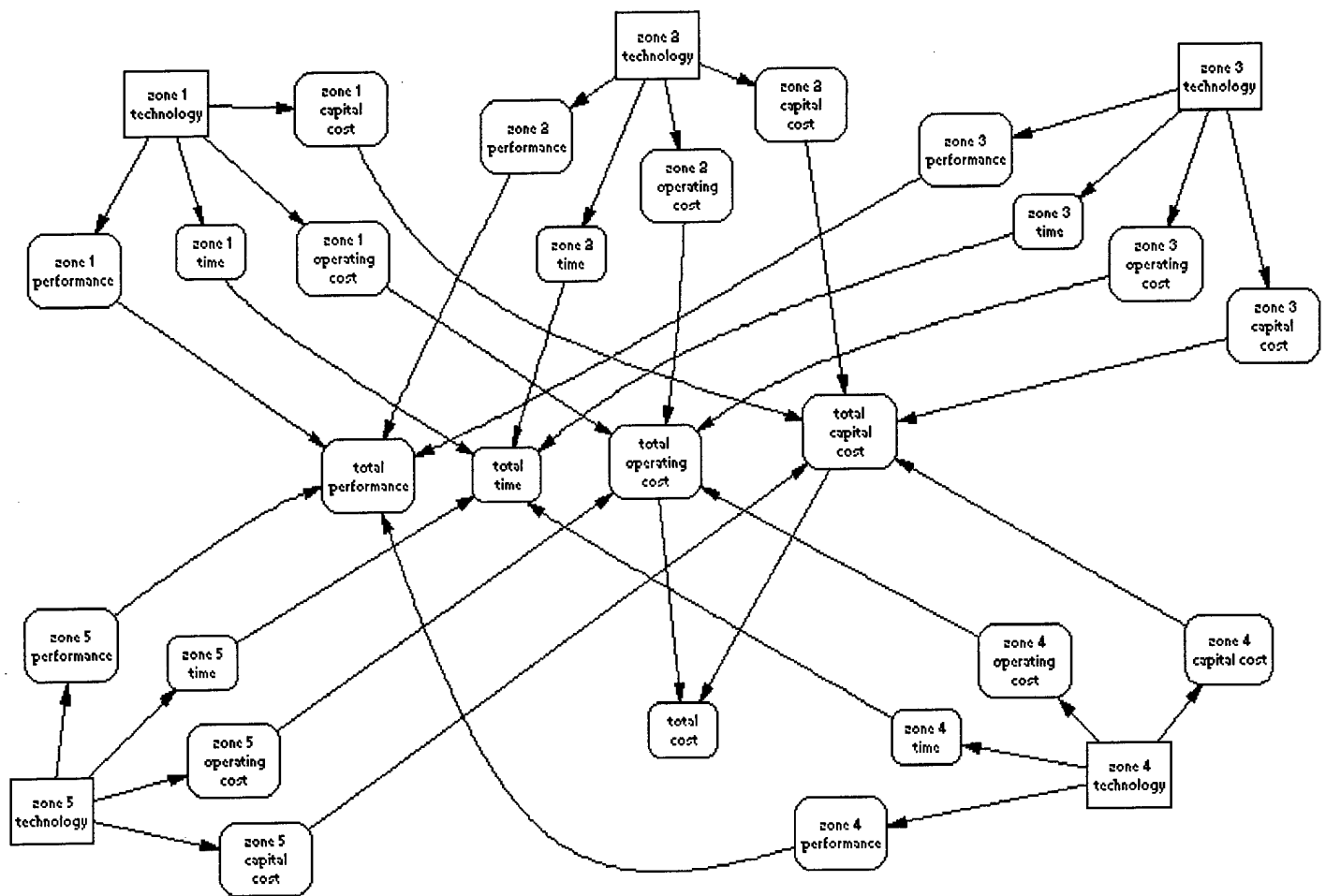
Figure G.2 Influence Diagram, Iteration 2

From Figure G.2 it is seen that the decision situation is broken into 5 separate zones. Each zone contains one decision - which technology to use in that particular zone. The zones are segregated based on hydrogeological characteristics, and cost (operating

and capital), time, and performance quantities are identified for each technology for each zone. These cost, time, and performance figures are then combined to determine totals (cost, time, and performance) for a complete strategy.

The model was discarded because of two major issues. The first was the number of potential combinations. Nine different technologies were identified for the first four zones, and eighteen were identified for zone 5. This meant that there were 118,098 (9^4 x 18) possible trains. This was far too many to evaluate individually, so an algorithm was developed to individually combine the 4 parameters (operating cost, capital cost, performance, and time). This led to the second issue. Because of the diversity of the technologies, a reasonable algorithm that combines individual technology parameters could not be agreed upon. The decision makers at the DOE were unable to accept the simple algorithms that were developed and could not provide alternative ones.

Iteration Number 3

Iteration no. 3 was a more accurate reflection of the decision situation. It contained a more realistic set of potential strategies. The influence diagram of this model is shown in Figure G.3.
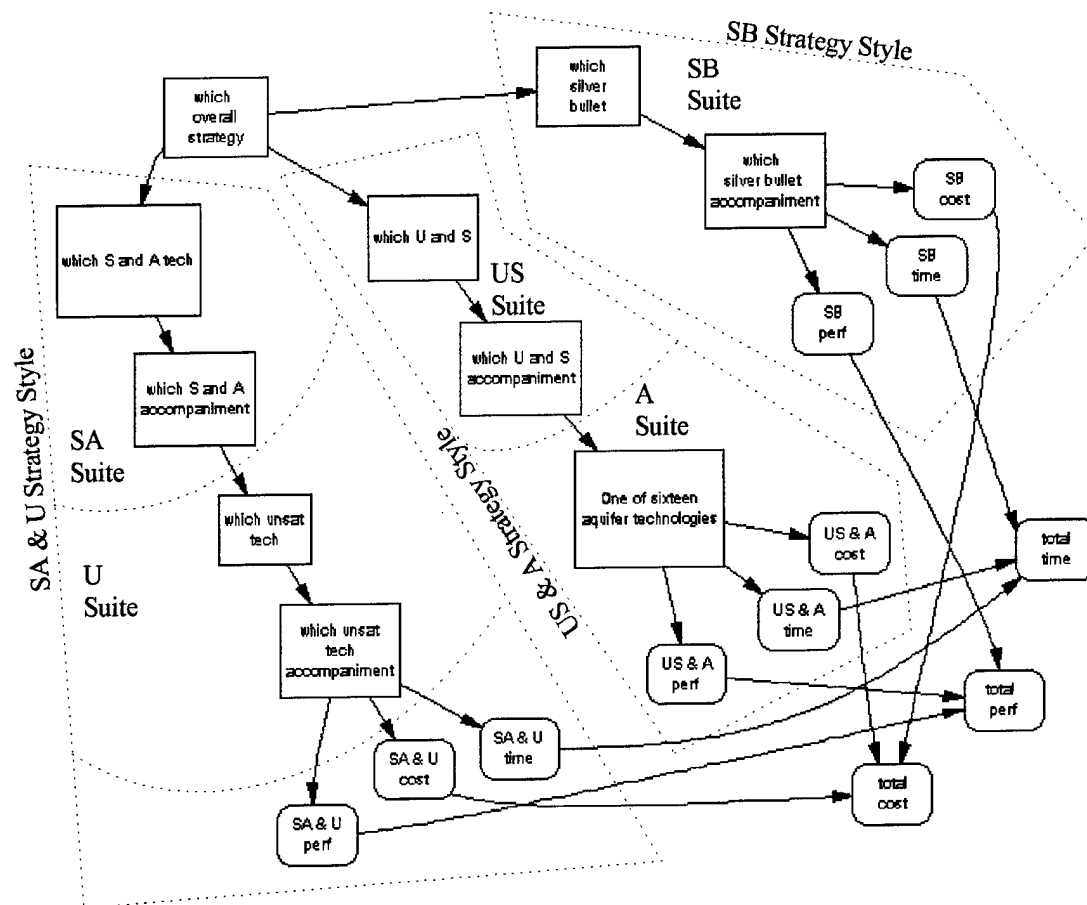
Figure G.3 Influence Diagram, Iteration 3

From this Figure, it is seen that the decision situation was been broken into three distinct pieces. Each piece represented a strategy style. This was a major change in the approach to this problem. The previous two versions focused on remediating specific zones or layers of subsurface. This model focused on realistic strategies developed through the iterative modeling process and have been categorized into one of three styles. These styles were thought to better depict the decision making thought process used at the DOE. The three styles were:

- USA (Silver Bullet - found in the upper right hand corner of Figure G.3) - This strategy style will remediate all of the contaminated zones. Note that at the time of this iteration, the USA trains were designated as SB or Silver Bullet Trains.

- US & A (Unsaturated, Saturated, and Aquifer - found in the center of Figure G.3) - This strategy style uses one technology suite for the unsaturated and saturated zones, and another suite for the aquifer.

- SA & U (Saturated, Aquifer, and Unsaturated - found on the right hand side of Figure G.3) - This strategy style uses one technology suite for the saturated zone and the aquifer, and uses another suite for the unsaturated zone.

An explanation of each of the nodes shown in Figure G.3 is found below in Table G.1.

Table G.1 Node Explanation for Figure G.3

Node Identifier	Node Type	Description
Which overall strategy	Decision	The decision here is between SB, US & A, and SA & U
Which silver bullet	Decision	The decision is between 3 SB primary technologies
Which silver bullet accompaniment	Decision	The decision is between 2 SB technology accompaniments
SB cost	Value	Contains cost data for SB strategies
SB time	Value	Contains time data for SB strategies
SB perf	Value	Contains performance data for SB strategies
Which U and S	Decision	The decision is to select one of 3 primary technologies to be used in the unsaturated and saturated zones
which U and S accompaniment	Decision	The decision is to select one of 4 technology accompaniments to be used in the unsaturated and saturated zones
One of sixteen aquifer technologies	Decision	The decision is to select one of 16 different technologies for the aquifer
US & A cost	Value	Contains cost data for US & A strategies
US & A time	Value	Contains time data for US & A strategies
US & A perf	Value	Contains performance data for US & A strategies
Which S and A tech	Decision	The decision is to select one of two primary technologies for the saturated zone and the aquifer
which S and A accompaniment	Decision	The decision is to select one of two technology accompaniments for the saturated zone and the aquifer
which unsat tech	Decision	The decision is to select one of two primary technologies for the unsaturated zone
which unsat tech accompaniment	Decision	The decision is to select one of four technology accompaniments for the unsaturated zone
SA & U cost	Value	Contains cost data for SA & U strategies
SA & U time	Value	Contains time data for SA & U strategies
SA & U perf	Value	Contains performance data for SA & U strategies
total time	Value	Represents the total amount of time required for a strategy
total perf	Value	Represents the total performance provided by a strategy
total cost		Represents the total cost required for a strategy

Each technology suite (SA, US, A, U, SB) is composed of a primary technology and a technology accompaniment. For example, one of the SA suites is PTZ and Bio. PTZ (Permeable Treatment Zones) is the primary technology, and bioremediation is the technology accompaniment.

Because of the complete enumeration of the data for each of the variables (cost, time, and performance), the details of the decision situation were model in a decision tree. The decision tree was developed in conjunction with the influence diagram. The structure of the decision tree is shown in Figure G.4. The purpose of Figure G.4 is to show the overall structure of the decision tree, not the details of the tree. A section of the detailed tree is found in Figure G.5.

Total Combination Count: 170

Silver Bullet Strategies

Area enlargened on next figure

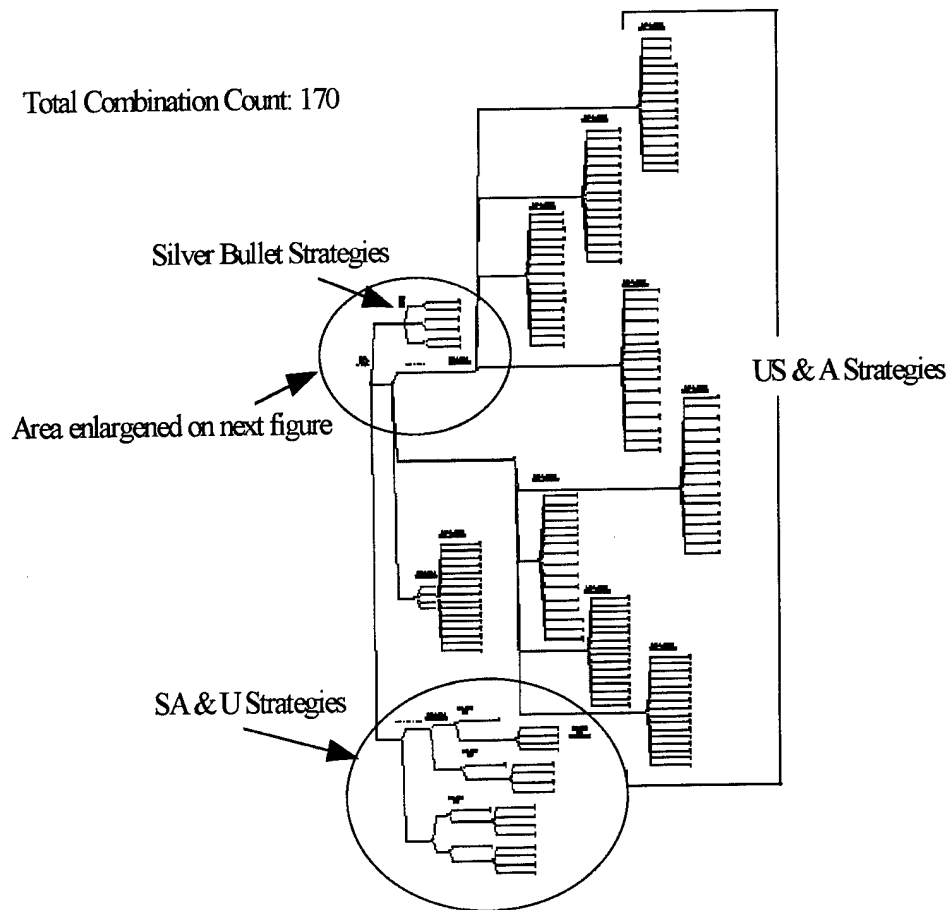US & A Strategies

SA & U Strategies
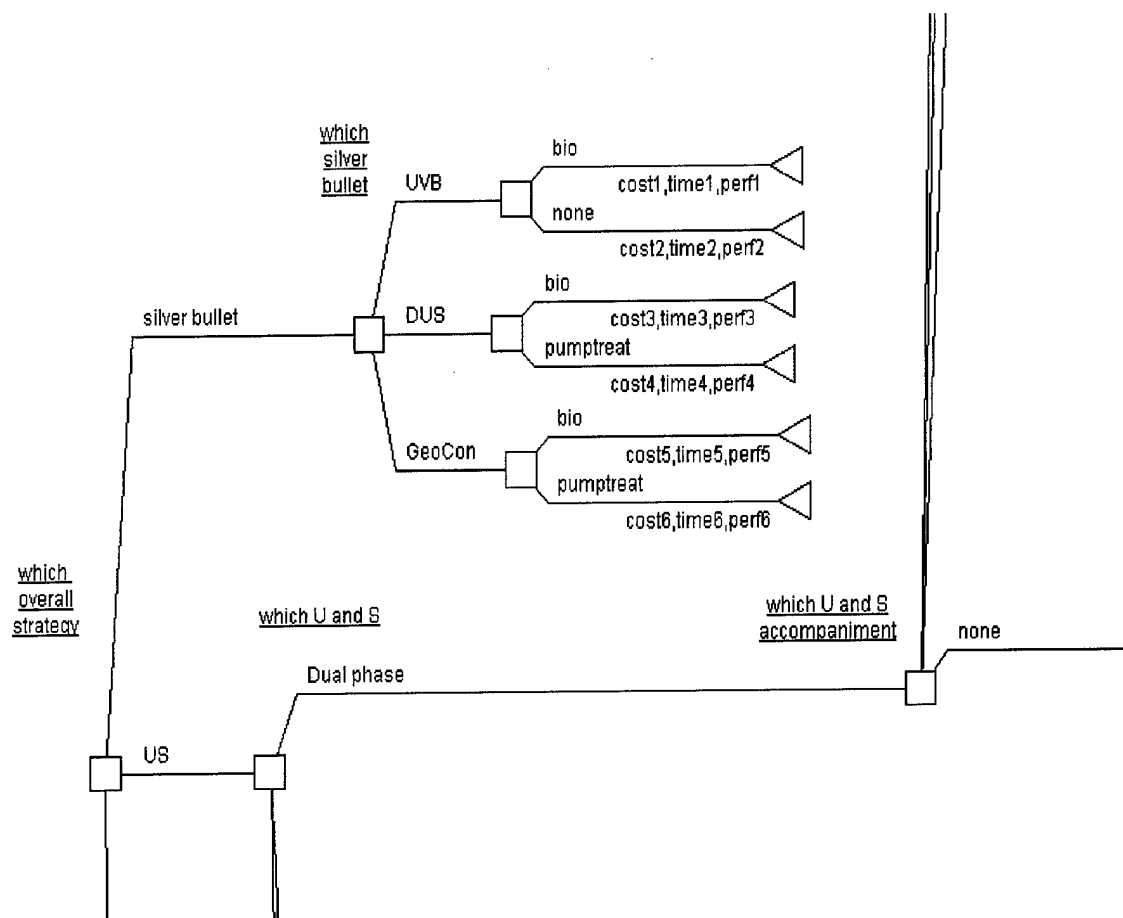
Figure G.4 Decision Tree Structure

Figure G.5 Enlarged Section of Decision Tree

From this point, the requisite screening model was built. This is completely described in

Chapter 3.

Appendix H DPL Listing Models

Screening Model:

```
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excel(Excel_1,"Sheet1!perf25") value perf25=0.9;
excel(Excel_1,"Sheet1!perf26") value perf26=0.77;
excel(Excel_1,"Sheet1!perf27") value perf27=0.99;
excel(Excel_1,"Sheet1!perf28") value perf28=0.97;
excel(Excel_1,"Sheet1!perf29") value perf29=0.99;
excel(Excel_1,"Sheet1!perf3") value perf3=1;
excel(Excel_1,"Sheet1!perf30") value perf30=0.98;
excel(Excel_1,"Sheet1!perf31") value perf31=0.88;
excel(Excel_1,"Sheet1!perf32") value perf32=0.8;
excel(Excel_1,"Sheet1!perf33") value perf33=0.92;
excel(Excel_1,"Sheet1!perf34") value perf34=0.84;
excel(Excel_1,"Sheet1!perf35") value perf35=0.99;
excel(Excel_1,"Sheet1!perf36") value perf36=0.98;
excel(Excel_1,"Sheet1!perf37") value perf37=0.88;
excel(Excel_1,"Sheet1!perf38") value perf38=0.75;
excel(Excel_1,"Sheet1!perf39") value perf39=0.98;
excel(Excel_1,"Sheet1!perf4") value perf4=1;
excel(Excel_1,"Sheet1!perf40") value perf40=0.95;
excel(Excel_1,"Sheet1!perf41") value perf41=0.96;
excel(Excel_1,"Sheet1!perf42") value perf42=0.95;
excel(Excel_1,"Sheet1!perf43") value perf43=0.85;
excel(Excel_1,"Sheet1!perf44") value perf44=0.77;
excel(Excel_1,"Sheet1!perf45") value perf45=0.89;
excel(Excel_1,"Sheet1!perf46") value perf46=0.81;

excel(Excel_1,"Sheet1!perf47") value perf47=0.96;
excel(Excel_1,"Sheet1!perf48") value perf48=0.95;
excel(Excel_1,"Sheet1!perf49") value perf49=0.85;
excel(Excel_1,"Sheet1!perf5") value perf5=0.99;
excel(Excel_1,"Sheet1!perf50") value perf50=0.72;
excel(Excel_1,"Sheet1!perf51") value perf51=0.95;
excel(Excel_1,"Sheet1!perf52") value perf52=0.92;
excel(Excel_1,"Sheet1!perf53") value perf53=0.99;
excel(Excel_1,"Sheet1!perf54") value perf54=0.99;
excel(Excel_1,"Sheet1!perf55") value perf55=0.95;
excel(Excel_1,"Sheet1!perf56") value perf56=0.87;
excel(Excel_1,"Sheet1!perf57") value perf57=0.99;
excel(Excel_1,"Sheet1!perf58") value perf58=0.91;
excel(Excel_1,"Sheet1!perf59") value perf59=0.99;
excel(Excel_1,"Sheet1!perf6") value perf6=0.99;
excel(Excel_1,"Sheet1!perf60") value perf60=0.99;
excel(Excel_1,"Sheet1!perf61") value perf61=0.95;
excel(Excel_1,"Sheet1!perf62") value perf62=0.82;
excel(Excel_1,"Sheet1!perf63") value perf63=0.99;
excel(Excel_1,"Sheet1!perf64") value perf64=0.99;
excel(Excel_1,"Sheet1!perf65") value perf65=0.64;
excel(Excel_1,"Sheet1!perf66") value perf66=0.8;
excel(Excel_1,"Sheet1!perf67") value perf67=0.8;
excel(Excel_1,"Sheet1!perf68") value perf68=0.75;
excel(Excel_1,"Sheet1!perf69") value perf69=0.7;
excel(Excel_1,"Sheet1!perf7") value perf7=0.9;
excel(Excel_1,"Sheet1!perf70") value perf70=0.4;
excel(Excel_1,"Sheet1!perf71") value perf71=0.5;
excel(Excel_1,"Sheet1!perf72") value perf72=0.5;
excel(Excel_1,"Sheet1!perf73") value perf73=0.45;
excel(Excel_1,"Sheet1!perf74") value perf74=0.42;
excel(Excel_1,"Sheet1!perf8") value perf8=0.82;
excel(Excel_1,"Sheet1!perf9") value perf9=0.94;
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excel(Excel_1,"Sheet1!time10") value time10=6;
excel(Excel_1,"Sheet1!time11") value time11=5.66666666666667;
excel(Excel_1,"Sheet1!time12") value time12=3;
excel(Excel_1,"Sheet1!time13") value time13=5.66666666666667;
excel(Excel_1,"Sheet1!time14") value time14=6;
excel(Excel_1,"Sheet1!time15") value time15=6.16666666666667;
excel(Excel_1,"Sheet1!time16") value time16=2.66666666666667;
excel(Excel_1,"Sheet1!time17") value time17=5.93060802369355;
excel(Excel_1,"Sheet1!time18") value time18=8.93060802369355;
excel(Excel_1,"Sheet1!time19") value time19=7.66666666666667;
excel(Excel_1,"Sheet1!time2") value time2=0.5;
excel(Excel_1,"Sheet1!time20") value time20=6;
excel(Excel_1,"Sheet1!time21") value time21=7.66666666666667;
excel(Excel_1,"Sheet1!time22") value time22=6;
excel(Excel_1,"Sheet1!time23") value time23=5.66666666666667;
excel(Excel_1,"Sheet1!time24") value time24=3;
excel(Excel_1,"Sheet1!time25") value time25=5.66666666666667;
excel(Excel_1,"Sheet1!time26") value time26=6;
excel(Excel_1,"Sheet1!time27") value time27=6.16666666666667;
excel(Excel_1,"Sheet1!time28") value time28=2.66666666666667;
excel(Excel_1,"Sheet1!time29") value time29=3.26394135702688;
excel(Excel_1,"Sheet1!time3") value time3=3.5;
excel(Excel_1,"Sheet1!time30") value time30=6.26394135702688;
excel(Excel_1,"Sheet1!time31") value time31=5;
excel(Excel_1,"Sheet1!time32") value time32=6;
excel(Excel_1,"Sheet1!time33") value time33=5;
excel(Excel_1,"Sheet1!time34") value time34=6;
excel(Excel_1,"Sheet1!time35") value time35=3;
excel(Excel_1,"Sheet1!time36") value time36=3;
excel(Excel_1,"Sheet1!time37") value time37=3;
excel(Excel_1,"Sheet1!time38") value time38=6;
excel(Excel_1,"Sheet1!time39") value time39=3.5;
excel(Excel_1,"Sheet1!time4") value time4=6.5;
excel(Excel_1,"Sheet1!time40") value time40=2.26666666666667;
excel(Excel_1,"Sheet1!time41") value time41=3.26394135702688;
excel(Excel_1,"Sheet1!time42") value time42=6.26394135702688;
excel(Excel_1,"Sheet1!time43") value time43=5;

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excel(Excel_1,"Sheet1!time44") value time44=6;
excel(Excel_1,"Sheet1!time45") value time45=5;
excel(Excel_1,"Sheet1!time46") value time46=6;
excel(Excel_1,"Sheet1!time47") value time47=3;
excel(Excel_1,"Sheet1!time48") value time48=3;
excel(Excel_1,"Sheet1!time49") value time49=3;
excel(Excel_1,"Sheet1!time5") value time5=5.93060802369355;
excel(Excel_1,"Sheet1!time50") value time50=6;
excel(Excel_1,"Sheet1!time51") value time51=3.5;
excel(Excel_1,"Sheet1!time52") value time52=2.16666666666667;
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excel(Excel_1,"Sheet1!time54") value time54=7.56438171941392;
excel(Excel_1,"Sheet1!time55") value time55=6.30044036238704;
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excel(Excel_1,"Sheet1!time57") value time57=6.30044036238704;
excel(Excel_1,"Sheet1!time58") value time58=7.30044036238704;
excel(Excel_1,"Sheet1!time59") value time59=4.30044036238704;
excel(Excel_1,"Sheet1!time6") value time6=8.93060802369355;
excel(Excel_1,"Sheet1!time60") value time60=4.30044036238704;
excel(Excel_1,"Sheet1!time61") value time61=4.30044036238704;
excel(Excel_1,"Sheet1!time62") value time62=7.30044036238704;
excel(Excel_1,"Sheet1!time63") value time63=4.80044036238704;
excel(Excel_1,"Sheet1!time64") value time64=1.80044036238704;
excel(Excel_1,"Sheet1!time65") value time65=3;
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excel(Excel_1,"Sheet1!time67") value time67=5.66666666666667;
excel(Excel_1,"Sheet1!time68") value time68=3;
excel(Excel_1,"Sheet1!time69") value time69=3;
excel(Excel_1,"Sheet1!time7") value time7=7.66666666666667;
excel(Excel_1,"Sheet1!time70") value time70=6;
excel(Excel_1,"Sheet1!time71") value time71=8.66666666666667;
excel(Excel_1,"Sheet1!time72") value time72=8.66666666666667;
excel(Excel_1,"Sheet1!time73") value time73=6;
excel(Excel_1,"Sheet1!time74") value time74=6;
excel(Excel_1,"Sheet1!time8") value time8=6;
excel(Excel_1,"Sheet1!time9") value time9=7.66666666666667;
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excel(Excel_1,"Sheet1!util10") value util10;
excel(Excel_1,"Sheet1!util11") value util11;
excel(Excel_1,"Sheet1!util12") value util12;
excel(Excel_1,"Sheet1!util13") value util13;
excel(Excel_1,"Sheet1!util14") value util14;
excel(Excel_1,"Sheet1!util15") value util15;
excel(Excel_1,"Sheet1!util16") value util16;
excel(Excel_1,"Sheet1!util17") value util17;
excel(Excel_1,"Sheet1!util18") value util18;
excel(Excel_1,"Sheet1!util19") value util19;
excel(Excel_1,"Sheet1!util2") value util2;
excel(Excel_1,"Sheet1!util20") value util20;
excel(Excel_1,"Sheet1!util21") value util21;
excel(Excel_1,"Sheet1!util22") value util22;
excel(Excel_1,"Sheet1!util23") value util23;
excel(Excel_1,"Sheet1!util24") value util24;
excel(Excel_1,"Sheet1!util25") value util25;
excel(Excel_1,"Sheet1!util26") value util26;
excel(Excel_1,"Sheet1!util27") value util27;
excel(Excel_1,"Sheet1!util28") value util28;
excel(Excel_1,"Sheet1!util29") value util29;
excel(Excel_1,"Sheet1!util3") value util3;
excel(Excel_1,"Sheet1!util30") value util30;
excel(Excel_1,"Sheet1!util31") value util31;
excel(Excel_1,"Sheet1!util32") value util32;
excel(Excel_1,"Sheet1!util33") value util33;
excel(Excel_1,"Sheet1!util34") value util34;
excel(Excel_1,"Sheet1!util35") value util35;
excel(Excel_1,"Sheet1!util36") value util36;
excel(Excel_1,"Sheet1!util37") value util37;
excel(Excel_1,"Sheet1!util38") value util38;
excel(Excel_1,"Sheet1!util39") value util39;
excel(Excel_1,"Sheet1!util4") value util4;
excel(Excel_1,"Sheet1!util40") value util40;
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excel(Excel_1,"Sheet1!util41") value util41;
excel(Excel_1,"Sheet1!util42") value util42;
excel(Excel_1,"Sheet1!util43") value util43;
excel(Excel_1,"Sheet1!util44") value util44;
excel(Excel_1,"Sheet1!util45") value util45;
excel(Excel_1,"Sheet1!util46") value util46;
excel(Excel_1,"Sheet1!util47") value util47;
excel(Excel_1,"Sheet1!util48") value util48;
excel(Excel_1,"Sheet1!util49") value util49;
excel(Excel_1,"Sheet1!util5") value util5;
excel(Excel_1,"Sheet1!util50") value util50;
excel(Excel_1,"Sheet1!util51") value util51;
excel(Excel_1,"Sheet1!util52") value util52;
excel(Excel_1,"Sheet1!util53") value util53;
excel(Excel_1,"Sheet1!util54") value util54;
excel(Excel_1,"Sheet1!util55") value util55;
excel(Excel_1,"Sheet1!util56") value util56;
excel(Excel_1,"Sheet1!util57") value util57;
excel(Excel_1,"Sheet1!util58") value util58;
excel(Excel_1,"Sheet1!util59") value util59;
excel(Excel_1,"Sheet1!util6") value util6;
excel(Excel_1,"Sheet1!util60") value util60;
excel(Excel_1,"Sheet1!util61") value util61;
excel(Excel_1,"Sheet1!util62") value util62;
excel(Excel_1,"Sheet1!util63") value util63;
excel(Excel_1,"Sheet1!util64") value util64;
excel(Excel_1,"Sheet1!util65") value util65;
excel(Excel_1,"Sheet1!util66") value util66;
excel(Excel_1,"Sheet1!util67") value util67;
excel(Excel_1,"Sheet1!util68") value util68;
excel(Excel_1,"Sheet1!util69") value util69;
excel(Excel_1,"Sheet1!util7") value util7;
excel(Excel_1,"Sheet1!util70") value util70;
excel(Excel_1,"Sheet1!util71") value util71;
excel(Excel_1,"Sheet1!util72") value util72;
excel(Excel_1,"Sheet1!util73") value util73;
excel(Excel_1,"Sheet1!util74") value util74;
excel(Excel_1,"Sheet1!util8") value util8;
excel(Excel_1,"Sheet1!util9") value util9;
decision Which_Strategy.{USA,US___A,SA___U};
decision USA_Primary_Technology_2_choices.{DUS,GTA};
decision USA_Secondary_Technology_2_choices.{Bio,Pump_treat};
decision US_Primary_Technology_2_choices.{two_phase,Lasagna};
decision US_Secondary_Technology_4_choices.{RF,six_phase,hydro,none};
decision
Aquifer_technology_12_choices.{oxid___bio,oxid___none,cosolvent___bio,cosolvent___none,surf___bio,surf___none,UVB___bio,UV
B___none,pump___bio,pump___none,PTZ___bio,PTZ___none};
decision Unsat_Primary_Technology_2_choices.{SVE,Two_phase};
decision Unsat_Secondary_Technology_4_choices.{RF,six_phase,hydro,none};
decision SA_Technology_2_choices.{Pump_treat___None,Pump_treat___Bio};
excel(Excel_1,"Sheet1!cost10") value cost10;
excel(Excel_1,"Sheet1!cost14") value cost14;
excel(Excel_1,"Sheet1!cost20") value cost20;
excel(Excel_1,"Sheet1!cost22") value cost22;
excel(Excel_1,"Sheet1!cost26") value cost26;
excel(Excel_1,"Sheet1!cost31") value cost31;
excel(Excel_1,"Sheet1!cost34") value cost34;
excel(Excel_1,"Sheet1!cost37") value cost37;
excel(Excel_1,"Sheet1!cost38") value cost38;
excel(Excel_1,"Sheet1!cost43") value cost43;
excel(Excel_1,"Sheet1!cost44") value cost44;
excel(Excel_1,"Sheet1!cost45") value cost45;
excel(Excel_1,"Sheet1!cost46") value cost46;
excel(Excel_1,"Sheet1!cost49") value cost49;
excel(Excel_1,"Sheet1!cost50") value cost50;
excel(Excel_1,"Sheet1!cost56") value cost56;
excel(Excel_1,"Sheet1!cost62") value cost62;
excel(Excel_1,"Sheet1!cost65") value cost65;
excel(Excel_1,"Sheet1!cost66") value cost66;
excel(Excel_1,"Sheet1!cost67") value cost67;
excel(Excel_1,"Sheet1!cost68") value cost68;
```

```
excel(Excel_1,"Sheet1!cost69") value cost69;
excel(Excel_1,"Sheet1!cost70") value cost70;
excel(Excel_1,"Sheet1!cost71") value cost71;
excel(Excel_1,"Sheet1!cost72") value cost72;
excel(Excel_1,"Sheet1!cost73") value cost73;
excel(Excel_1,"Sheet1!cost74") value cost74;
excel(Excel_1,"Sheet1!cost8") value cost8;
excel(Excel_1,"Sheet1!import_cost_wt") value import_cost_wt;
excel(Excel_1,"Sheet1!import_perf_wt") value import_perf_wt;
excel(Excel_1,"Sheet1!import_time_wt") value import_time_wt;
excel(Excel_1,"Sheet1!om10") value om10;
excel(Excel_1,"Sheet1!om14") value om14;
excel(Excel_1,"Sheet1!om20") value om20;
excel(Excel_1,"Sheet1!om22") value om22;
excel(Excel_1,"Sheet1!om26") value om26;
excel(Excel_1,"Sheet1!om31") value om31;
excel(Excel_1,"Sheet1!om32") value om32;
excel(Excel_1,"Sheet1!om34") value om34;
excel(Excel_1,"Sheet1!om37") value om37;
excel(Excel_1,"Sheet1!om38") value om38;
excel(Excel_1,"Sheet1!om43") value om43;
excel(Excel_1,"Sheet1!om44") value om44;
excel(Excel_1,"Sheet1!om45") value om45;
excel(Excel_1,"Sheet1!om46") value om46;
excel(Excel_1,"Sheet1!om49") value om49;
excel(Excel_1,"Sheet1!om50") value om50;
excel(Excel_1,"Sheet1!om56") value om56;
excel(Excel_1,"Sheet1!om62") value om62;
excel(Excel_1,"Sheet1!om65") value om65;
excel(Excel_1,"Sheet1!om66") value om66;
excel(Excel_1,"Sheet1!om67") value om67;
excel(Excel_1,"Sheet1!om68") value om68;
excel(Excel_1,"Sheet1!om69") value om69;
excel(Excel_1,"Sheet1!om70") value om70;
excel(Excel_1,"Sheet1!om71") value om71;
excel(Excel_1,"Sheet1!om72") value om72;
excel(Excel_1,"Sheet1!om73") value om73;
excel(Excel_1,"Sheet1!om74") value om74;
excel(Excel_1,"Sheet1!om8") value om8;

sequence( attributes = 5,
          objective = $5 ):


decide
        to Which_Strategy.USA then decide
                to USA_Primary_Technology_2_choices.DUS then decide
                        to USA_Secondary_Technology_2_choices.Bio and get cost1,time1,perf1,om1,util1
                        to USA_Secondary_Technology_2_choices.Pump_treat and get cost2,time2,perf2,om2,util2
                to USA_Primary_Technology_2_choices.GTA then decide
                        to USA_Secondary_Technology_2_choices.Bio and get cost3,time3,perf3,om3,util3
                        to USA_Secondary_Technology_2_choices.Pump_treat and get cost4,time4,perf4,om4,util4
        to Which_Strategy.US___A then decide
                to US_Primary_Technology_2_choices.two_phase then decide
                        to US_Secondary_Technology_4_choices.RF then decide
                                to Aquifer_technology_12_choices.oxid___bio and get cost5,time5,perf5,om5,util5
                                to Aquifer_technology_12_choices.oxid___none and get cost6,time6,perf6,om6,util6
                                to Aquifer_technology_12_choices.cosolvent___bio and get cost7,time7,perf7,om7,util7
                                to Aquifer_technology_12_choices.cosolvent___none and get cost8,time8,perf8,om8,util8
                                to Aquifer_technology_12_choices.surf___bio and get cost9,time9,perf9,om9,util9
                                to Aquifer_technology_12_choices.surf___none and get cost10,time10,perf10,om10,util10
                                to Aquifer_technology_12_choices.UVB___bio and get cost11,time11,perf11,om11,util11
                                to Aquifer_technology_12_choices.UVB___none and get cost12,time12,perf12,om12,util12
                                to Aquifer_technology_12_choices.pump___bio and get cost13,time13,perf13,om13,util13
                                to Aquifer_technology_12_choices.pump___none and get
cost14,time14,perf14,om14,util14
                                to Aquifer_technology_12_choices.PTZ___bio and get cost15,time15,perf15,om15,util15
                                to Aquifer_technology_12_choices.PTZ___none and get cost16,time16,perf16,om16,util16
                        to US_Secondary_Technology_4_choices.six_phase then decide
                                to Aquifer_technology_12_choices.oxid___bio and get cost17,time17,perf17,om17,util17
                                to Aquifer_technology_12_choices.oxid___none and get cost18,time18,perf18,om18,util18
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to Aquifer_technology_12_choices.cosolvent___bio and get

cost19,time19,perf19,om19,util19

to Aquifer_technology_12_choices.cosolvent___none and get

cost20,time20,perf20,om20,util20

to Aquifer_technology_12_choices.surf___bio and get cost21,time21,perf21,om21,util21
to Aquifer_technology_12_choices.surf___none and get cost22,time22,perf22,om22,util22
to Aquifer_technology_12_choices.UVB___bio and get cost23,time23,perf23,om23,util23
to Aquifer_technology_12_choices.UVB___none and get cost24,time24,perf24,om24,util24
to Aquifer_technology_12_choices.pump___bio and get cost25,time25,perf25,om25,util25
to Aquifer_technology_12_choices.pump___none and get

cost26,time26,perf26,om26,util26

to Aquifer_technology_12_choices.PTZ___bio and get cost27,time27,perf27,om27,util27
to Aquifer_technology_12_choices.PTZ___none and get cost28,time28,perf28,om28,util28
to US_Secondary_Technology_4_choices.hydro then decide
to Aquifer_technology_12_choices.oxid___bio and get cost29,time29,perf29,om29,util29
to Aquifer_technology_12_choices.oxid___none and get cost30,time30,perf30,om30,util30
to Aquifer_technology_12_choices.cosolvent___bio and get

cost31,time31,perf31,om31,util31

to Aquifer_technology_12_choices.cosolvent___none and get

cost32,time32,perf32,om32,util32

to Aquifer_technology_12_choices.surf___bio and get cost33,time33,perf33,om33,util33
to Aquifer_technology_12_choices.surf___none and get cost34,time34,perf34,om34,util34
to Aquifer_technology_12_choices.UVB___bio and get cost35,time35,perf35,om35,util35
to Aquifer_technology_12_choices.UVB___none and get cost36,time36,perf36,om36,util36
to Aquifer_technology_12_choices.pump___bio and get cost37,time37,perf37,om37,util37
to Aquifer_technology_12_choices.pump___none and get

cost38,time38,perf38,om38,util38

to Aquifer_technology_12_choices.PTZ___bio and get cost39,time39,perf39,om39,util39
to Aquifer_technology_12_choices.PTZ___none and get cost40,time40,perf40,om40,util40
to US_Secondary_Technology_4_choices.none then decide
to Aquifer_technology_12_choices.oxid___bio and get cost41,time41,perf41,om41,util41
to Aquifer_technology_12_choices.oxid___none and get cost42,time42,perf42,om42,util42
to Aquifer_technology_12_choices.cosolvent___bio and get

cost43,time43,perf43,om43,util43

to Aquifer_technology_12_choices.cosolvent___none and get

cost44,time44,perf44,om44,util44

to Aquifer_technology_12_choices.surf___bio and get cost45,time45,perf45,om45,util45
to Aquifer_technology_12_choices.surf___none and get cost46,time46,perf46,om46,util46
to Aquifer_technology_12_choices.UVB___bio and get cost47,time47,perf47,om47,util47
to Aquifer_technology_12_choices.UVB___none and get cost48,time48,perf48,om48,util48
to Aquifer_technology_12_choices.pump___bio and get cost49,time49,perf49,om49,util49
to Aquifer_technology_12_choices.pump___none and get

cost50,time50,perf50,om50,util50

to Aquifer_technology_12_choices.PTZ___bio and get cost51,time51,perf51,om51,util51
to Aquifer_technology_12_choices.PTZ___none and get cost52,time52,perf52,om52,util52
to US_Primary_Technology_2_choices.Lasagna then decide
to US_Secondary_Technology_4_choices.none then decide
to Aquifer_technology_12_choices.oxid___bio and get cost53,time53,perf53,om53,util53
to Aquifer_technology_12_choices.oxid___none and get cost54,time54,perf54,om54,util54
to Aquifer_technology_12_choices.cosolvent___bio and get

cost55,time55,perf55,om55,util55

to Aquifer_technology_12_choices.cosolvent___none and get

cost56,time56,perf56,om56,util56

to Aquifer_technology_12_choices.surf___bio and get cost57,time57,perf57,om57,util57
to Aquifer_technology_12_choices.surf___none and get cost58,time58,perf58,om58,util58
to Aquifer_technology_12_choices.UVB___bio and get cost59,time59,perf59,om59,util59
to Aquifer_technology_12_choices.UVB___none and get cost60,time60,perf60,om60,util60
to Aquifer_technology_12_choices.pump___bio and get cost61,time61,perf61,om61,util61
to Aquifer_technology_12_choices.pump___none and get

cost62,time62,perf62,om62,util62

to Aquifer_technology_12_choices.PTZ___bio and get cost63,time63,perf63,om63,util63
to Aquifer_technology_12_choices.PTZ___none and get cost64,time64,perf64,om64,util64
to US_Secondary_Technology_4_choices.{RF,six_phase,hydro} and get 99999999,999,0,0,0
to Which_Strategy.SA___U then decide
to SA_Technology_2_choices.Pump_treat___None then decide
to Unsat_Primary_Technology_2_choices.SVE and get cost70,time70,perf70,om70,util70
to Unsat_Primary_Technology_2_choices.Two_phase then decide
to Unsat_Secondary_Technology_4_choices.RF and get cost71,time71,perf71,om71,util71
to Unsat_Secondary_Technology_4_choices.six_phase and get

cost72,time72,perf72,om72,util72

to Unsat_Secondary_Technology_4_choices.hydro and get

cost73,time73,perf73,om73,util73

to Unsat_Secondary_Technology_4_choices.none and get

cost74,time74,perf74,om74,util74

        to SA_Technology_2_choices.Pump_treat___Bio then decide

           to Unsat_Primary_Technology_2_choices.SVE and get cost65,time65,perf65,om65,util65

           to Unsat_Primary_Technology_2_choices.Two_phase then decide

                to Unsat_Secondary_Technology_4_choices.RF and get cost66,time66,perf66,om66,util66

                to Unsat_Secondary_Technology_4_choices.six_phase and get

cost67,time67,perf67,om67,util67

to Unsat_Secondary_Technology_4_choices.hydro and get

cost68,time68,perf68,om68,util68

to Unsat_Secondary_Technology_4_choices.none and get

cost69,time69,perf69,om69,util69

Phase 2 Model:

```
string Excel_1="c:\\winword\\tony\\thesis\\test202.xls";
excel(Excel_1,"Sheet1!export_cost_wt") value export_cost_wt=0.44;
excel(Excel_1,"Sheet1!export_perf_wt") value export_perf_wt=0.44;
excel(Excel_1,"Sheet1!export_time_wt") value export_time_wt=0.12;
excel(Excel_1,"Sheet1!import_cost_wt") value import_cost_wt;
excel(Excel_1,"Sheet1!import_perf_wt") value import_perf_wt;
excel(Excel_1,"Sheet1!import_time_wt") value import_time_wt;
value cost_utility_factor=30000000;
value performance_utility_factor=.9;
value Performance_Desired=.95;
value Interest_Rate=.025;
value Performance_Utility=@if(Performance_Desired>performance_utility_factor,(Performance_Desired-
performance_utility_factor)*10,0);
decision Which_Train.{no__3,no__4,no__94,no__119,no__135,no__148,no__156};
chance Time_Required.{Low,Med,High}|Which_Train=
        {.185,.63,.185},       // Which_Train.no__3
        {.185,.63,.185},       // Which_Train.no__4
        {.185,.63,.185},       // Which_Train.no__94
        {.185,.63,.185},       // Which_Train.no__119
        {.185,.63,.185},       // Which_Train.no__135
        {.185,.63,.185},       // Which_Train.no__148
        {.185,.63,.185},       // Which_Train.no__156

=
                                                        // Which_Train.no__3
        @if(Performance_Desired<=.99,-7.93+10.52*Performance_Desired,1000),    //    Time_Required.Low
        @if(Performance_Desired<=.99,-15.86+21.03*Performance_Desired,1000),   //    Time_Required.Med
        @if(Performance_Desired<=.99,-29.15+39.39*Performance_Desired,1000),   //    Time_Required.High
                                                        // Which_Train.no__4
        @if(Performance_Desired<=.9,81.22*pow(Performance_Desired,22.45),1000), //   Time_Required.Low
        @if(Performance_Desired<=.9,182.77*pow(Performance_Desired,23.03),1000),   //    Time_Required.Med
        @if(Performance_Desired<=.9,287.93*pow(Performance_Desired,21.12),1000),   //    Time_Required.High
                                                        // Which_Train.no__94
        @if(Performance_Desired<=.9,.16*@exp(Performance_Desired*4.54),1000),   //    Time_Required.Low
        @if(Performance_Desired<=.9,.33*@exp(Performance_Desired*4.54),1000),   //    Time_Required.Med
        @if(Performance_Desired<=.9,.66*@exp(Performance_Desired*4.54),1000),   //    Time_Required.High
                                                        // Which_Train.no__119
        @if(Performance_Desired<=.99,2.13+7.1*@ln(Performance_Desired),1000),   //    Time_Required.Low
        @if(Performance_Desired<=.99,-11.64+15.77*Performance_Desired,1000),    //    Time_Required.Med
        @if(Performance_Desired<=.99,8.61*pow(Performance_Desired,5.47),1000),  //    Time_Required.High
                                                        // Which_Train.no__135
        @if(Performance_Desired<=.95,-2.75+5*Performance_Desired,1000),         //    Time_Required.Low
        @if(Performance_Desired<=.95,.14*@exp(Performance_Desired*3.47),1000),  //    Time_Required.Med
        @if(Performance_Desired<=.95,9.87*pow(Performance_Desired,4.15),1000),  //    Time_Required.High
                                                        // Which_Train.no__148
        @if(Performance_Desired<=.99,63.05*pow(Performance_Desired,1.99),1000), //    Time_Required.Low
        @if(Performance_Desired<=.99,77.16+158.78*@ln(Performance_Desired),1000),   //    Time_Required.Med
        @if(Performance_Desired<=.99,2.03*@exp(Performance_Desired*3.91),1000),     //    Time_Required.High
                                                        // Which_Train.no__156
        @if(Performance_Desired<=.99,1.73*@exp(Performance_Desired*3.73),1000),     //    Time_Required.Low
        @if(Performance_Desired<=.99,77.16+158.78*@ln(Performance_Desired),1000),   //    Time_Required.Med
        @if(Performance_Desired<=.99,2.03*@exp(Performance_Desired*3.91),1000);     //    Time_Required.High
value Capital_Cost|Which_Train=
        243206,                 // Which_Train.no__3
        2134837,                // Which_Train.no__4
        2470812,                // Which_Train.no__94
        1193059,                // Which_Train.no__119
        323972,                 // Which_Train.no__135
        2019759,                // Which_Train.no__148
        988418;                 // Which_Train.no__156
value O_M_Cost|Which_Train,Time_Required=
                                                // Which_Train.no__3
        @pv(336558,Interest_Rate,Time_Required), //    Time_Required.Low
        @pv(336558,Interest_Rate,Time_Required), //    Time_Required.Med
        @pv(336558,Interest_Rate,Time_Required), //    Time_Required.High
                                                // Which_Train.no__4
        @pv(203820,Interest_Rate,Time_Required), //    Time_Required.Low
        @pv(203820,Interest_Rate,Time_Required), //    Time_Required.Med
```

```
        @pv(203820,Interest_Rate,Time_Required), //        Time_Required.High
                                                                   // Which_Train.no__94
        @pv(625713,Interest_Rate,Time_Required), //        Time_Required.Low
        @pv(625713,Interest_Rate,Time_Required), //        Time_Required.Med
        @pv(625713,Interest_Rate,Time_Required), //        Time_Required.High
                                                                   // Which_Train.no__119
        @pv(1056083,Interest_Rate,Time_Required),          //      Time_Required.Low
        @pv(1056083,Interest_Rate,Time_Required),          //      Time_Required.Med
        @pv(1056083,Interest_Rate,Time_Required),          //      Time_Required.High
                                                                   // Which_Train.no__135
        @pv(737648,Interest_Rate,Time_Required), //        Time_Required.Low
        @pv(737648,Interest_Rate,Time_Required), //        Time_Required.Med
        @pv(737648,Interest_Rate,Time_Required), //        Time_Required.High
                                                                   // Which_Train.no__148
        @pv(103537,Interest_Rate,Time_Required), //        Time_Required.Low
        @pv(103537,Interest_Rate,Time_Required), //        Time_Required.Med
        @pv(103537,Interest_Rate,Time_Required), //        Time_Required.High
                                                                   // Which_Train.no__156
        @pv(316627,Interest_Rate,Time_Required), //        Time_Required.Low
        @pv(316627,Interest_Rate,Time_Required), //        Time_Required.Med
        @pv(316627,Interest_Rate,Time_Required); //        Time_Required.High
value NPV_Cost=O_M_Cost+Capital_Cost;
value Cost_Utility=@if(NPV_Cost<30000000,1-(1/cost_utility_factor)*NPV_Cost,.7-.00000002*NPV_Cost);
value Time_Utility|Time_Required=
        @if(Time_Required<6,1,@if(Time_Required>18,0,1.5-.083333*Time_Required)),      // Time_Required.Low
        @if(Time_Required<6,1,@if(Time_Required>18,0,1.5-.083333*Time_Required)),      // Time_Required.Med
        @if(Time_Required<6,1,@if(Time_Required>18,0,1.5-.083333*Time_Required));      // Time_Required.High
value Overall_Utility=import_cost_wt*Cost_Utility+import_time_wt*Time_Utility+import_perf_wt*Performance_Utility;

sequence( attributes = 9,
          objective = $5 ):


set Which_Train.no__135 and get Capital_Cost,Performance_Desired,Performance_Utility,0,0,0,0,0,0 then
gamble on Time_Required and get 0,0,0,O_M_Cost,NPV_Cost,Time_Required,Cost_Utility,Time_Utility,Overall_Utility
```
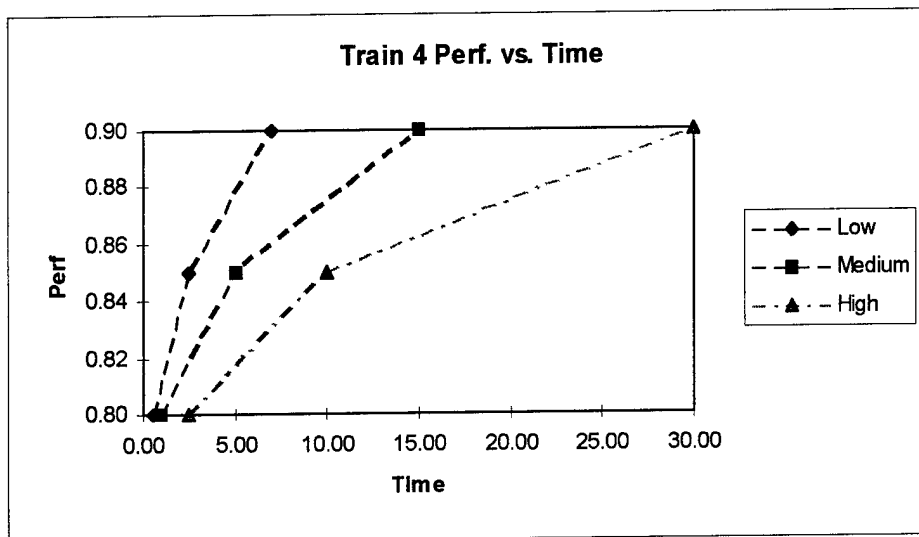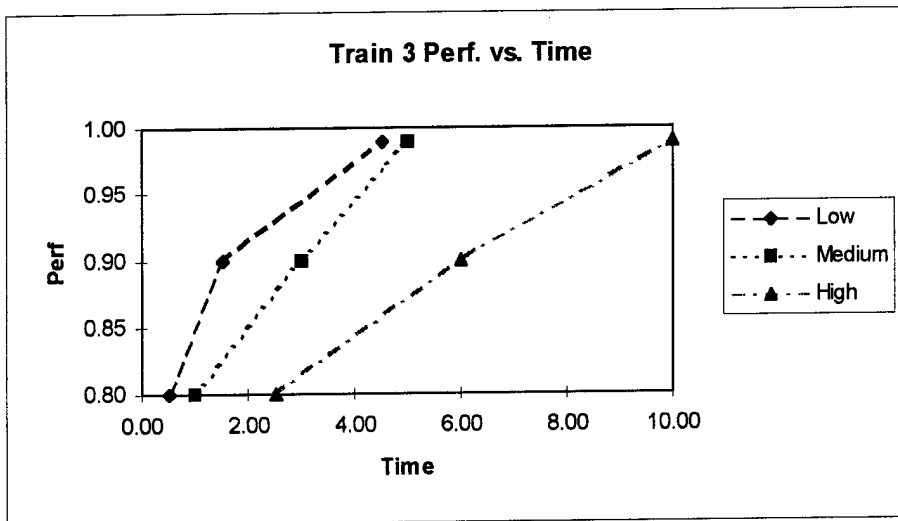
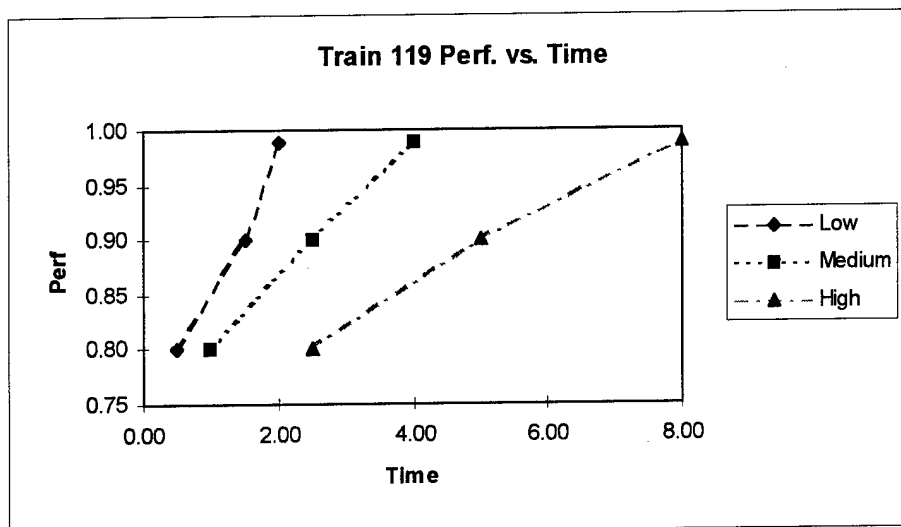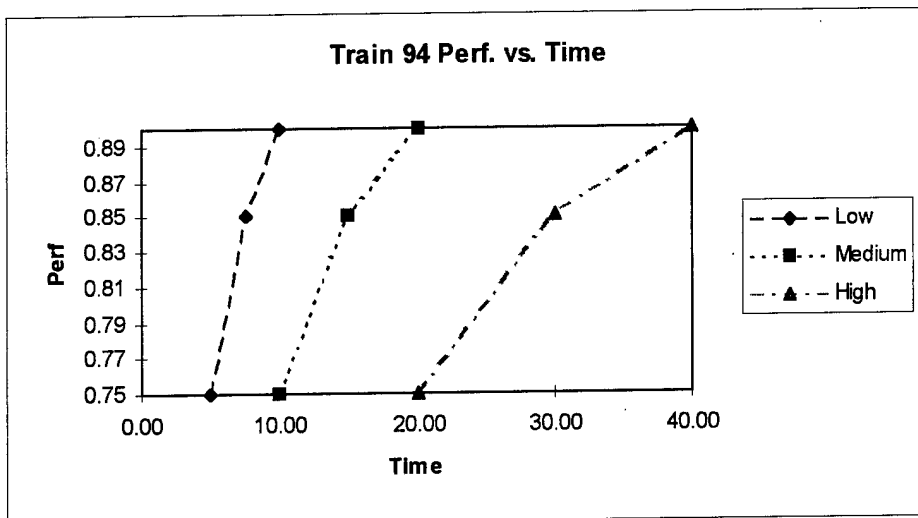Table I.1 contains data developed on 23 Jan 97 during a trip to Paducah

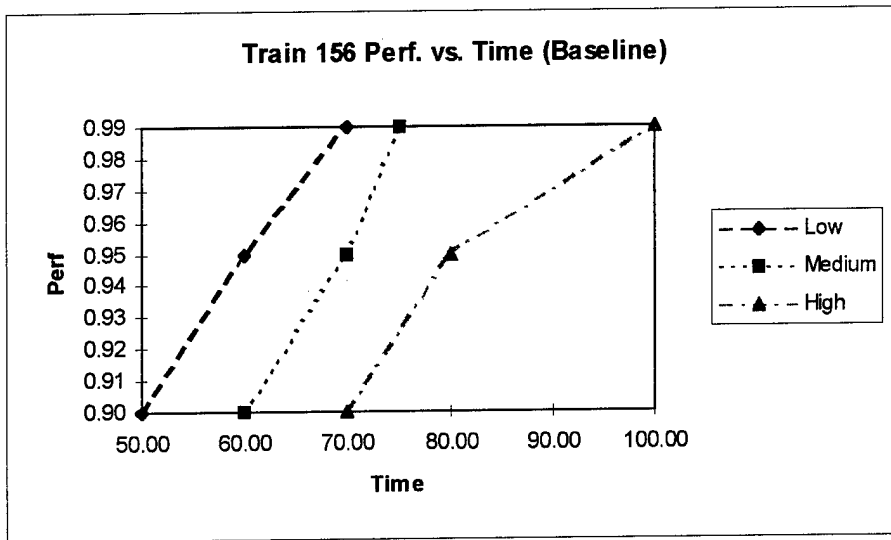| Train		80%			90%			99%		
	Low	Med	High	Low	Med	High	Low	Med	High	DUS for half - Bio for the rest
3	0.5	1.0	2.5	1.5	3.0	6.0	2.5	5.0	10.0	series
Train		80%			85%			90%		DUS 0.5 to .9, Pump and treat
	Low	Med	High	Low	Med	High	Low	Med	High	doesn't help
4	0.5	1.0	2.5	2.5	5.0	10.0	7.0	15.0	30.0	series
Train		75%			85%			90%		UVB doesn't go quick for
	Low	Med	High	Low	Med	High	Low	Med	High	3rd zone - good for first two
94	5.0	10.0	20.0	7.5	15.0	30.0	10.0	20.0	40.0	parallel
Train		80%			90%			99%		Oxidation followed by bio is
	Low	Med	High	Low	Med	High	Low	Med	High	critical
119	0.5	1.0	2.5	1.5	2.5	5.0	2.0	4.0	8.0	parallel
Train		75%			85%			95%		Bugs must wait for oxidation
	Low	Med	High	Low	Med	High	Low	Med	High	to clear
135	1.0	2.0	3.0	1.5	2.5	5.0	2.0	4.0	8.0	Series
Train		90%			95%			99%		Barrier must wait for source to
	Low	Med	High	Low	Med	High	Low	Med	High	dissolve
148	50.0	60.0	70.0	60.0	70.0	80.0	60.0	75.0	100.0	Series
Train		90%			95%			99%		
	Low	Med	High	Low	Med	High	Low	Med	High	
156	50.0	60.0	70.0	60.0	70.0	80.0	70.0	75.0	100.0	Parallel

The data in Table I.1 was developed through a session with technical experts at the DOE. The high, low, and medium values were determined through this panel of experts, then the data was reviewed independently by another group of experts.

Plots of the raw data follow:

Train 3 Perf. vs. Time

Train 4 Perf. vs. Time

Train 94 Perf. vs. Time

Train 119 Perf. vs. Time

Train 135 Perf. vs. Time

Train 148 Perf. vs. Time

Train 156 Perf. vs. Time (Baseline)
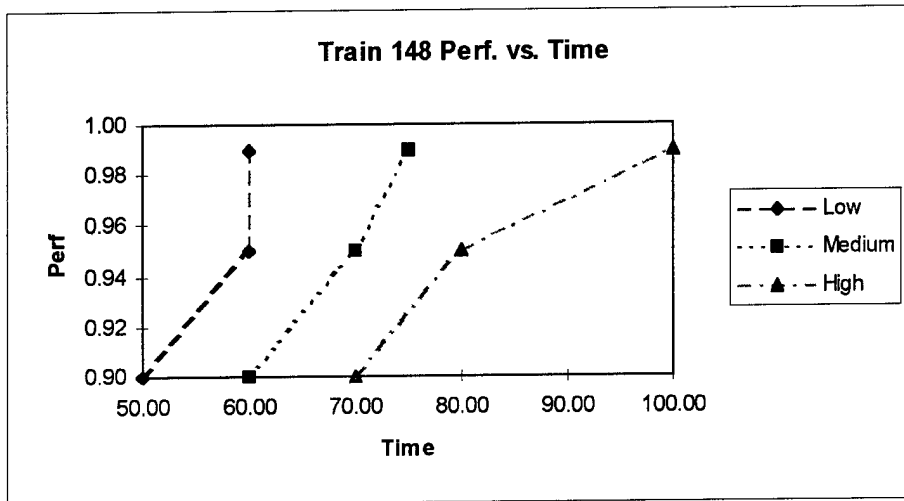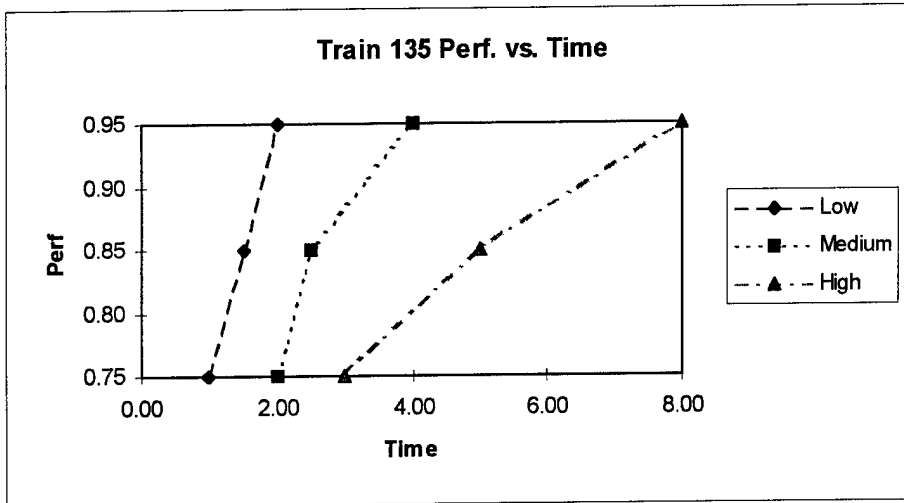
The data points shown above were fit using the following regression equations:

Exponential equations are of the form: $y = ae^{bx}$
Power equations are of the form: $y = ax^b$
Linear equations are of the form: $y = a + bx$
Logarithmic equations are of the form: $y = a + b(\ln x)$

$$An + b\Sigma X_i = \Sigma Y_i$$
$$A\Sigma X_i + b\Sigma(X_i)^2 = \Sigma(Y_i X_i)$$
where:

Regression	A	X_i	Y_i
Exponential	$\ln(a)$	x_i	$\ln(y_i)$
Power	$\ln(a)$	$\ln(x_i)$	$\ln(y_i)$
Linear	a	x_i	y_i
Logarithmic	a	$\ln(x_i)$	y_i

Train 3

In terms of time as a function of performance:

time = -7.93+10.52*perf   low   f(x)
time = -15.86+21.03*perf   med   g(x)
tme = -29.15+39.39*perf   high   h(x)
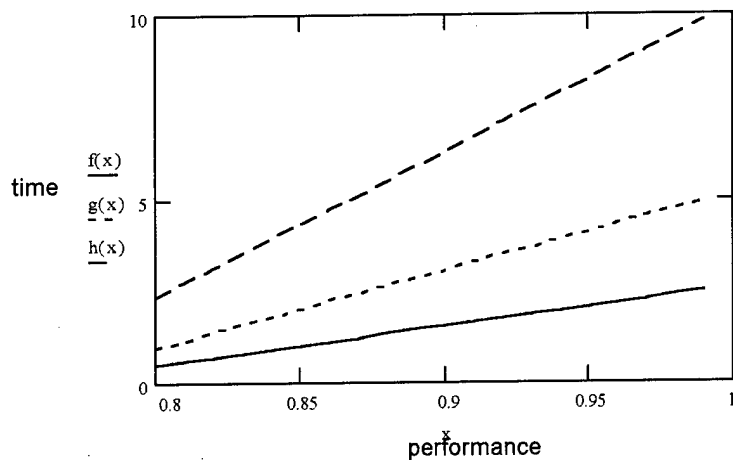
Train 4

In terms of time as a function of performance:

time = 81.22*perf$^{22.45}$	low	f(t)
time = 182.77*perf$^{23.03}$	med	g(t)
tme = 287.93*perf$^{21.12}$	high	h(t)

time

$\dfrac{f(t)}{}$
$\underline{g(t)}$
$\underline{h(t)}$
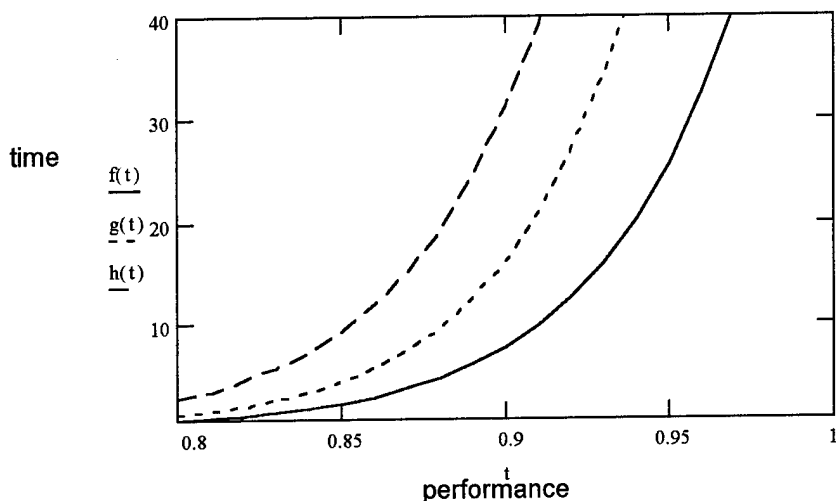
performance

Train 94

In terms of time as a function of performance:

time = 0.16*e$^{4.54*perf}$	low	f(t)
time = 0.33*e$^{4.54*perf}$	med	g(t)
tme = 0.66*e$^{4.54*perf}$	high	h(t)

time

$\dfrac{f(t)}{}$
$\underline{g(t)}$
$\underline{h(t)}$
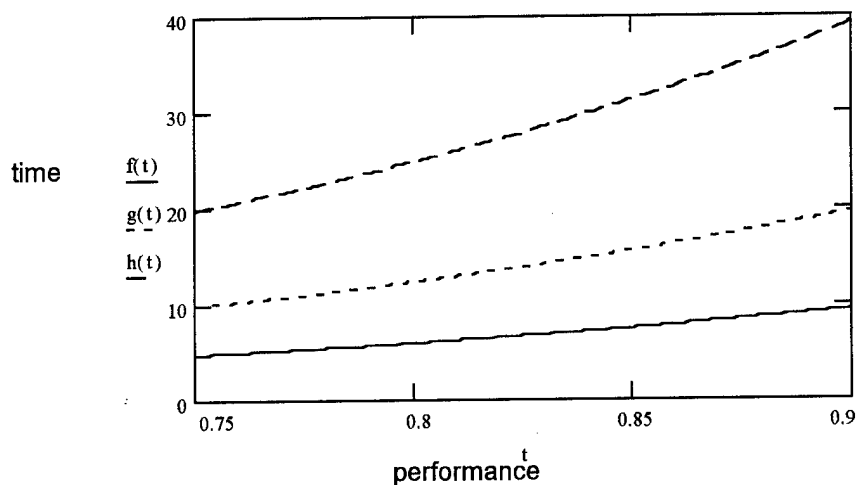
performance

Train 119

In terms of time as a function of performance:

time = 2.13+7.10*ln(perf)   low   f(t)

time = -11.64+15.77*perf   med   g(t)

tme = 8.61*perf$^{5.47}$ high   h(t)
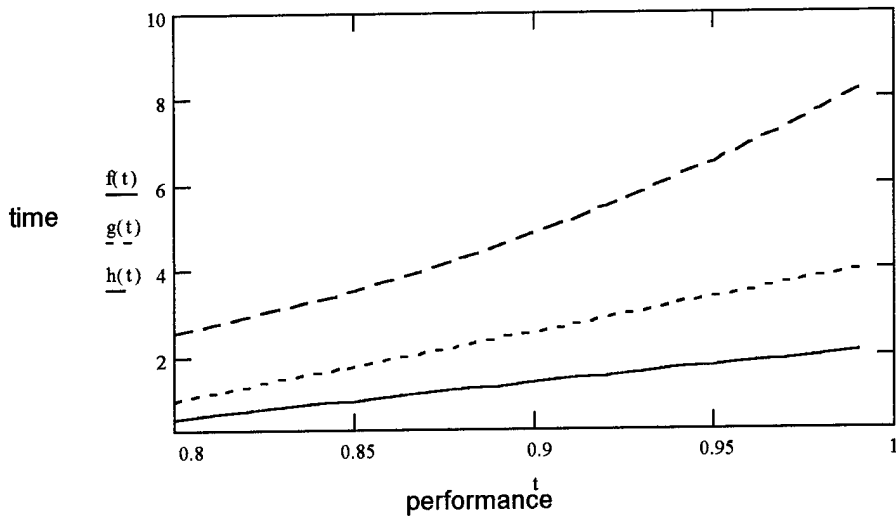
Train 135

In terms of time as a function of performance:

time = -2.75+5*perf   low   f(t)

time = 0.14*e$^{3.47*perf}$ med   g(t)

tme = 9.87*perf$^{4.15}$ high   h(t)
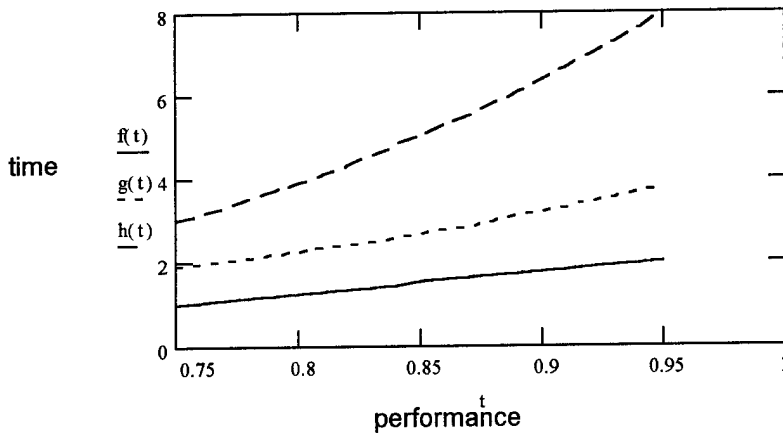
Train 148

In terms of time as a function of performance:

time = 63.05*perf$^{1.99}$	low	f(y)
time = 77.16+158.78*ln(perf)	med	g(y)
tme = 2.03*e$^{3.91*perf}$	high	h(y)
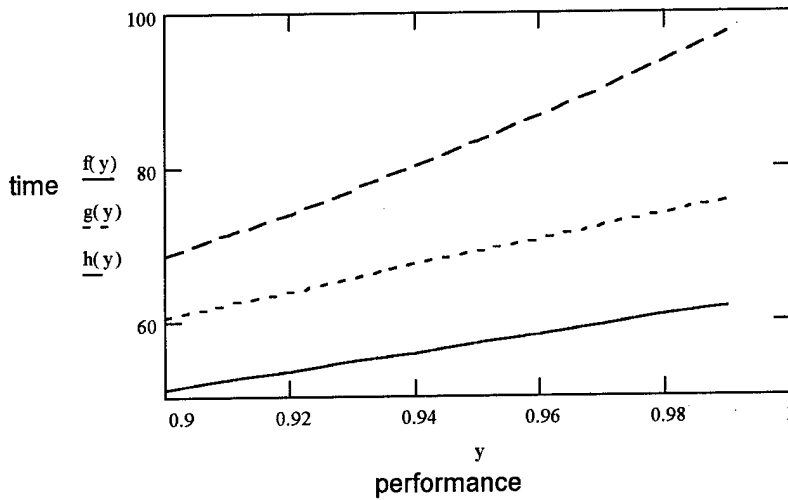
Train 156

In terms of time as a function of performance:

time = 1.73*e$^{3.73*perf}$	low	f(y)
time = 77.16+158.78*ln(perf)	med	g(y)
tme = 2.03*e$^{3.91*perf}$	high	h(y)
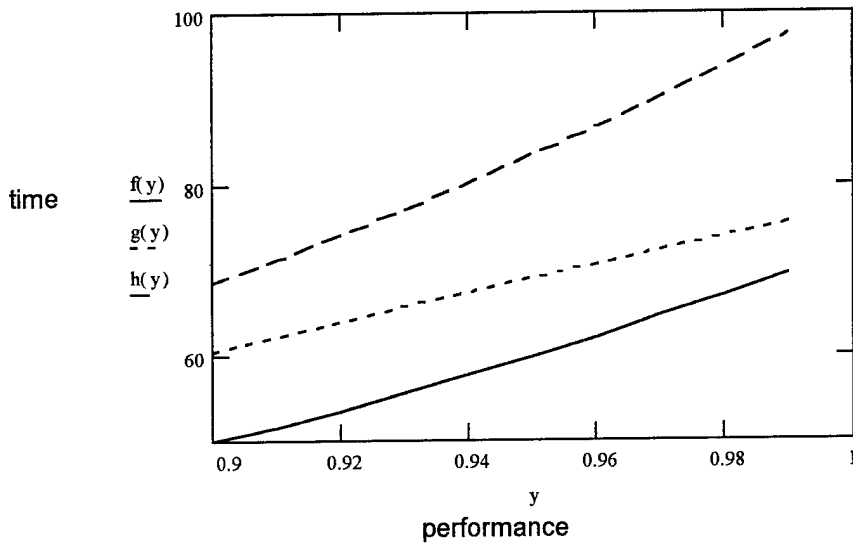
Appendix J Spill Volume Information

Because of the uncertain nature of estimating the volume of a contaminant spill,

many approximations have been created. Shown below are two such approximations.

The first one, Figure J.1 shows the initial estimate of the spill volume. Figure J.2 shows

another estimate. Because of the uncertainty surrounding this issue, and because of the

lack of availability of scaleable data, neither of the two estimates were used. Instead, a

point estimate of 7,500 gallons was used to estimate the cost, time, and performance

values. It is these values (the ones based on 7,500 gallons) that were used as a data basis

for the analysis contained in this thesis effort.

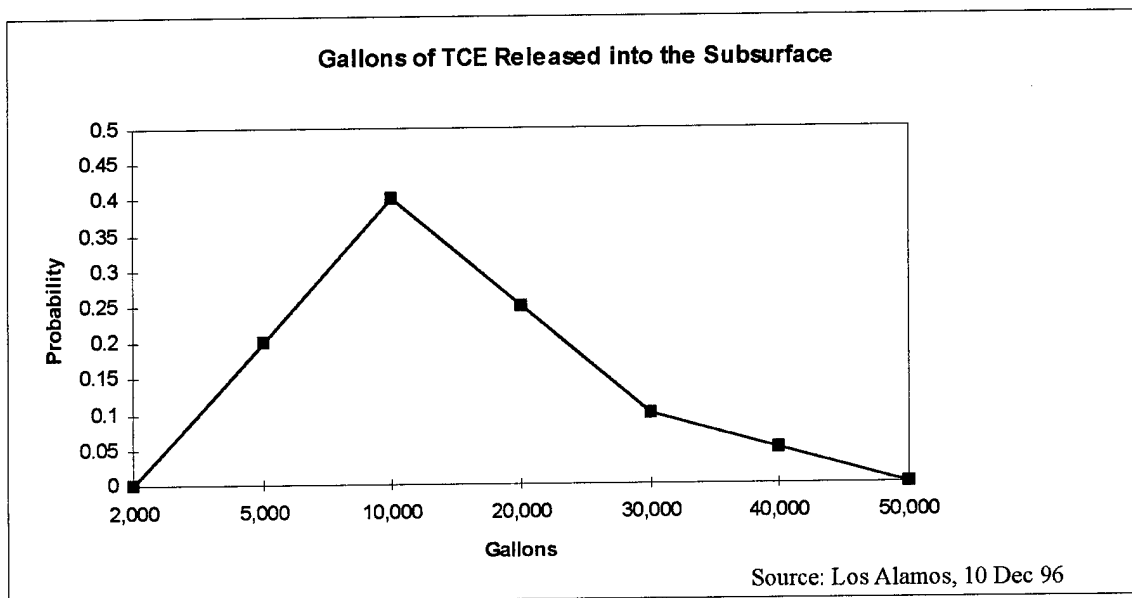**Gallons of TCE Released into the Subsurface**

Source: Los Alamos, 10 Dec 96

Figure J.1 Initial Estimate of Spill Volume

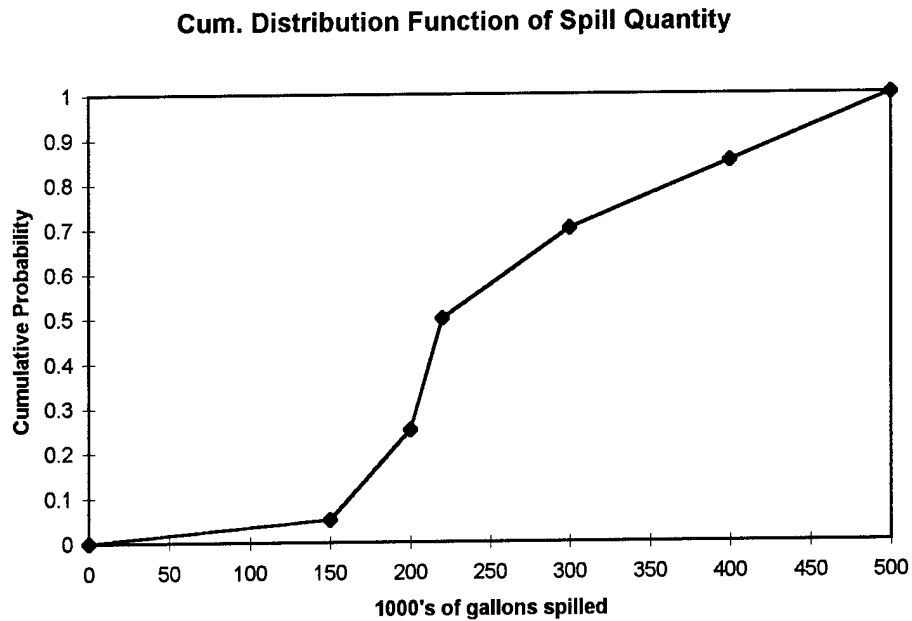**Cum. Distribution Function of Spill Quantity**

Figure J.2 Another Estimate of the Spill Volume - Acquired
During 23 Jan 97 Trip to Paducah

Bibliography

Allert, L. and T. Bennet and J.H. Lehr and R.J. Petty and G. Hackett. "DRASTIC: A Standardized System for Evaluating Groundwater Pollution Potential Using Hydrogeologic Settings," Report no. 600/2-87-035, U.S EPA, Ada, OK.

Apostolakis, George and David C. Bell "Modeling the Public as a Stakeholder in Environmental Risk Decision Making," IEEE Internaltional Conference on Systems, Man and Cybernetics. Intelligent Systems for the 21st Century. pp. 1021-1026. New York: IEEE Press, 1995.

Blacker, Stanley and Daniel Goodman. "An Integrated Approach for Efficient Site Cleanup," Environmental Science Technology, Volume 28, no. 11: pp. 466 - 470 (1994).

-----. "Case Study: Application at a Superfund Cleanup," Environmental Science Technology, Volume 28, no. 11: pp. 471 - 477 (1994).

Burns, Thomas J. and Marland Thurston and Michael H. Edgar. "Case Study: Using a Parametric Model for Environmental Remediation Cost Estimating," Federal Facilities Environmental Journal. pp. 51-62, Summer 1995.

Cardwell, Hal and Dale Huff and Jeff Douthitt and Mike Sale. A Case Study of Optimization in the Decision Process: Siting Ground Water Monitoring Wells. Contract no. DE-AC05-84OR21400. Martin Marietta Energy Systems, Inc. December, 1993.

Chenu, Marie T. and Jacqueline A. Crenca. "The Cost of Remedial Action Model," Expert Systems for Environmental Applications. J.M. Hushon Edition, American Chemical Society, Washington, D.C. 1990.

Clayton, Bryan. Technical Expert, Jacobs Engineering Company, Paducah, Kentucky. Telephone interview. 10 Feb 97.

Clemen, Robert T. Making Hard Decisions, An Introduction to Decision Analysis. Belmont, CA: Duxbury Press, 1996.

Cohen, Robert M. and James W. Mercer. DNAPL Site Evaluation. Boca Raton, FL: CRC Press, Inc. 1993.

Department of Energy. Contaminant Plumes Containment and Remediation Focus Area Technology Summary. June 1995. DOE/EM-0248.

Department of Energy. Plumes and Landfill Focus Area Progress Report. Winter 1996.

Department of Energy. <u>Integrated Remedial Investigation/Feasibility Study Work Plan for Waste Area Grouping 6 at Paducah Gaseous Diffusion Plant Paducah, Kentucky.</u> August 1996. DOE/OR/07-1243&D3.

Department of the Air Force, Headquarters Aeronautica Systems Center, Wright-Patterson Air Force Base, Ohio. <u>Final Record of Decision: Air Force Plant 4, Tarrant County, Texas.</u> July 1996. GJPO-TP-11.

<u>DPL.</u> Advanced Version, IBM, 1.2 Mbyte diskette, Computer Software, ADA Decision Systems, Menlo Park, CA. 1995.

Droppo, J.G. and B.L. Hoopes. "Remedial Action Priority and Multimedia Environmental Pollutant Assessment System." <u>Expert Systems for Environmental Applications.</u> J.M. Hushon edition, American Chemical Society, Washington, D.C. 1990.

Environmental Protection Agency. <u>Citizen's Guide to Soil Washing.</u> EPA/542/F-92/003. March, 1992.

Environmental Protection Agency. <u>Remediation Technologies Screening Matrix.</u> EPA/542/B-94/013. October, 1994.

Evans, E.K. and G.M. Duffield, Geraghty and Miller Modeling Group. Massman, J.W., University of Washington. Freeze, R.A., R.A. Freeze Engineering, Inc. Stephenson, D.E., Westinghouse Savannah River Company. <u>Demonstration of Risk Based Decision Analysis in Remedial Alternative Selection and Design.</u> August, 1994

<u>Expert Systems for Environmental Applications.</u> J.M. Hushon edition, American Chemical Society, Washington, D.C. 1990

Falta, R.W. and T.R. Jarosch and Kueper B.H. and Looney B.B. and Sabitini D.A. and Siegrist R.L. and K.S. Udell. <u>Technical Evaluation of DNAPL Enhanced Removal Technologies.</u> June 1996.

Freeze, R. Allen and Joel Massman and Leslie Smith and Tony Sperling and Bruce James. "Hydrogeological Decision Analysis," <u>Groundwater.</u> pp. 111-123, Groundwater Publishing Company, 1992.

Greathouse, D. and J. Clements. "PAST: The Potential ARARs Selection Tool," Proceedings of <u>Hazardous Material Control/Superfund '91.</u> Hazardous Materials Control Research Institute, pp. 632-636, Washington, D.C. 1991.

Hartz, K.E. and G. Whelan. "MEPAS and RAAS Methodologies as integrated into the RI/EA/FS Process," Proceedings of Superfund '88. Hazardous Materials Control Research Institute, pp. 246-256. Washington, D.C. 1988.

Holloway, Charles A. Decision Making Under Uncertainty: Models and Choices. Englewood Cliffs, NJ. Prentice Hall. 1979.

Howard, Ronald A. "Decision Analysis: Practice and Promise". , Management Science. Vol. 34. No. 6. pp. 679-695. June, 1988.

Hudson, K.K. and R.F Shangraw. "U.S. DOE's Program to Better Understand the Cost of Environmental Restoration Projects," Proceedings of Superfund '90. Hazardous Materials Control Research Institute, pp. 762-778. Washington, D.C. 1990

Hushon, J.M. "The Defense Priority Model for Department of Defense Remedial Site Ranking," Expert Systems for Environmental Applications. J.M. Hushon edition, American Chemical Society, pp. 562-580. Washington, D.C. 1990.

Jennings, Aaron A. and Neel Mehta and Sumeet Mohan. "Superfund Decision Analysis in Presence of Uncertainty," Journal of Environmental Engineering. Vol. 120, No. 5. pp. 1132-1150, Sept/Oct 1994.

Keeney, Ralph L. Value Focused Thinking. Cambrideg Massachusetts. Harvard University Press. 1992

Mather, John. "Technology Summary", September 1995 WWWeb http://www.em.doe.gov/plumesfa/intech/dus/sum.hmtl.

Merkhofer, M.W. and T.A. Cotton and T.P Longo. "A Program Optimization System for Aiding Decisions to Fund the Cleanup of Hazardous Waste Sites at Department of Energy Facilities," Proceedings of Superfund '88. Hazardous Materials Control Research Institute, pp. 124-146. Washington, D.C. 1988.

National Research Council. Alternatives for Groundwater Cleanup. National Academy Press, Washington D.C. 1995

Parnell, Gregory S. Cost and Development Risk Guidance for Principal Investigators in the Subsurface Contaminants Focus Area. Contract no. 96-C342-CR. MSE Technology Applications, Inc. August, 1996.

Purucker, S.T. and B.F. Lyon and R.N. Stewart and L.D. Nanstad. <u>Decision Support for CERCLA Investigations: An Introduction to Decision Analysis Applications.</u> Contract DE-AC05-84OR21400. Martin Marietta Energy Systems, Inc. September, 1994.

Rossman, L.A. and T.J. Siller. "Expert Systems in Environmental Engineering," <u>Expert Systems for Civil Engineers: Technology and Application.</u> M.L Maher Edition. pp. 1024-1036. ASCE New York, NY. 1987.

Ralston, Brian E. <u>Development of a Decision Support System for the Department of Energy's Selection of Waste Site Remediation Technologies.</u> MS Thesis, AFIT/GOR/ENS/96M. School of Engineering, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, March, 1996. (ADA311013).

Scott, Dennis J. <u>Groundwater Modeling: Application of a Multiphase Fluid Flow Model as a Decision Making Tool for Assessing and Remediating Installation Restoration Program Sites.</u> MS Thesis, AFIT/GEE/ENV/93S-15. School of Engineering, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, September 1993.

Smith, L.A. and C.D. Patrick and C.M. Hudson. "Human Exposure Potential Ranking Model". <u>Proceedings of Superfund '87.</u> Hazardous Materials Control Research Institute, 158-161, Washington, D.C. 1987.

Stewart, Theodore J. "Simplified Approaches for Multicriteria Decision Making Under Uncertainty," <u>Journal of Multi-Criteria Decision Analysis,</u> Vol 4. pp. 246-258. 1995.

Stripe, J.A. and Kazuyoshi Arisaka and Marc Durandeau. "Integrated Field Development Planning Using Risk and Decision Analysis to Minimize the Impact of Reservoir and Other Uncertaintities: A Case Study". <u>Proceedings of the Middle East Oil Show.</u> v.1, 1993. Published by the Society of Petroleum Engineers of AIME, 155-167, Richardson, TX.

Timm, Christopher M. "Systematic Decision Making: A Route to Reasonable Remediation," <u>The National Environmental Journal.</u> pp. 46-53, November/December, 1995.

Timmerman, Thomas, J. <u>Estimating Risks in Emerging Soil Remediation Technologies.</u> MS Thesis. AFIT/GOA/ENS/96M-09. School of Engineering, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, March, 1996.

Walls, Michael R. and Thomas G. Morahan and James S. Dyer. "Decision Analysis of Exploration Opportunities in the Onshore US at Phillips Petroleum Company," <u>Interfaces.</u> 25: 6 November, pp. 39-56, December 1995.

Wells, S. and S. Caldwell. "Overview of the Revised Hazard Ranking System (HRS)". Proceedings of <u>Superfund '90.</u> Hazardous Materials Control Research Institute, Washington, D.C. 1990.

West, Olivia R. Principle Investigator at Oak Ridge National Laboratory for In-situ Chemical Oxidation of Soils. E- Mail: qm5@ornl.gov. Oct 1996.

White, Thomas P. and Ronald J. Toland and Dorian Y. Buitrago. <u>Life Cycle Cost Analysis for Radioactive Waste Remediation Alternatives.</u> MS Thesis. AFIT/GOA/GOR/ENS/95M-50. School of Engineering, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, March, 1995.

Wu, J.S. and H. Hilger. "Evaluation of EPA's Hazard Ranking System," <u>Journal of Environmental Engineering.</u> pp. 896-912. ASCE, 1984

Vita

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13. ABSTRACT *(Maximum 200 words)*

The Department of Energy is in the process of conducting a Remedial Investigation/Feasibility Study for a site contaminated with Dense Non-Aqueous Phase Liquid (DNAPL) pollutants at their Paducah Kentucky facility. A major part of this effort is the screening of alternative technologies. This thesis effort focuses on acquiring insight into a number of remediation technology trains that are candidates for the Paducah site. This insight is used to recommend and justify the screening of candidate technology trains. The research makes use of two decision analysis models (one is deterministic, the other is probabilistic) built to provide a quantitative assessment of the candidate technology trains. Dominance considerations and multi-attribute utility theory are utilized to make the quantitative assessments and to gain insight into each candidate technology train.

The results of the analysis provide the DOE with a rational justification for screening 55 of the 58 candidate technology trains from further consideration. This represents a 95% reduction in the number of technology trains that are under consideration for remediating the Paducah site.

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